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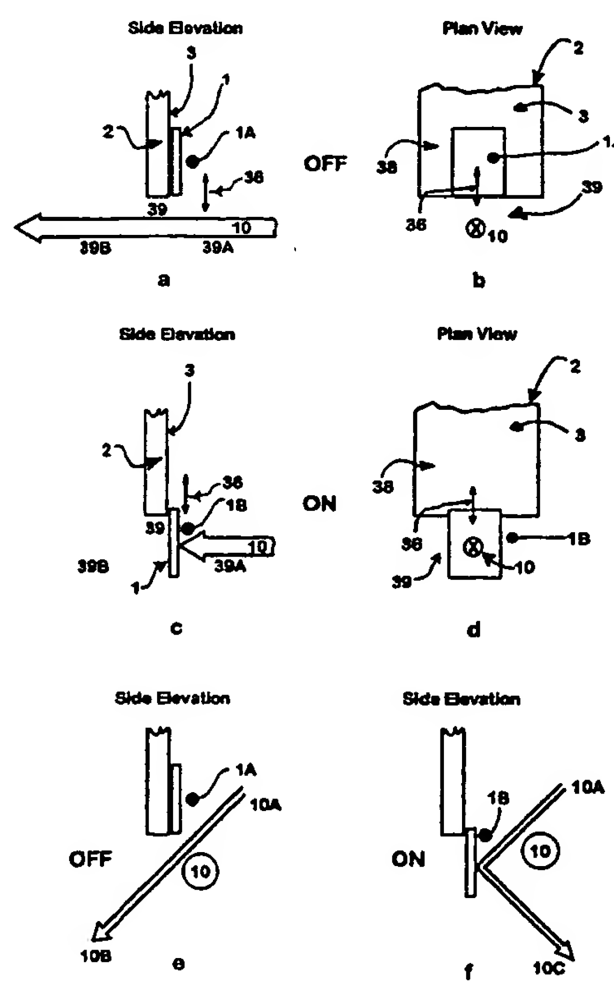
(54) Title: OPTO-MECHANICAL VALVE AND VALVE ARRAY FOR FIBER-OPTIC COMMUNICATION



(57) Abstract: A microelectromechanical system optical switch is introduced which includes a mirror (1) constructed on a substrate (3). The mirror (1) is movable parallel to the surface of the substrate and either allows an input ray incident at an oblique angle, preferably 45°, to the mirror surface (1) to pass undisturbed through a transparent part of a substrate or reflects the ray to an alternate output.

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OPTO-MECHANICAL VALVE AND VALVE ARRAY FOR FIBER-OPTIC COMMUNICATION

Field and Background of the Invention

The present invention relates to switching in optical networks, such as optical communications networks, to an optomechanical valve, and to arrays of optical valves generally.

An essential component of any communications system is a switch to enable signal routing. Various types of devices are used for optical switching. Some transform the optical signal into the electrical domain, where switching is done, and then retransform back to the optical domain. Others use integrated optics to perform switching, using materials such as lithium niobate. These devices are relatively expensive, their minimum size is limited by the physics of optical wave-guides, they are strongly dependent on wavelength, and they suffer from cross-talk and signal attenuation.

One way to overcome many of these limitations is to use mechanical optical switches (Motamedi M. E. *et al.* "Micro-opto-electro-mechanical devices and on-chip optical processing", *Optical Engineering* vol. 36 No. 5, May 1997, page 1282, and other articles in this issue of the journal). Micro-mechanical switches are not wavelength dependent and can be very compact. Signal loss occurs mainly at the input from and output into the fibers, which is about the same as for other switching technologies. The medium of propagation between fibers, typically air but possibly vacuum or inert gases, accounts for only a very small portion of the attenuation.

The valves and valve arrays of the present invention overcome the shortfalls of previous art.

Summary of the Invention

A micro-electromechanical optical switch using a movable mirror constructed on the surface of a substrate and oriented at 45° to the ray's direction is presented. The switch either intercepts a light ray and reflects the ray into a changed direction or allows the ray to transit unimpeded. This switch is situated on, above, inside, or below a substrate and actuated parallel to the substrate's surface by electrostatic, magnetic, thermal, piezoelectric, or other means. Some of these bi-stable actuation methods, which may be utilized in other applications, are described below. In the case of electrostatic actuation, an envelope-style electrode may be used to obtain larger forces than are obtained in prior art configurations, such as comb actuators, to produce faster switching. Designing the electrode edges to have a more complicated or irregular shape such as a fractal shape can increase this force even more. It should be noted that the terms "valve" and "switch" are used interchangeably herein.

An N×N switch, that can route any of its N inputs to any of its N outputs, is simple to realize. There is no interference among the N inputs, since light-ray paths cross without interaction (Hecht J., "Optical switching promises cure for telecommunications log-jam". *Laser Focus World*, September 1998, page 69). There is thus almost no cross-talk between data lines, which allows the utilization of such switches in complicated schemes. Such switches may be incorporated into a three-dimensional array in order to produce compact cross-connects that may switch rays from a plurality of inputs to any of a plurality of outputs, a configuration that can be utilized in optical computation. They may also be used to switch other than optical waves, for example acoustic waves. A three-dimensional switch array disclosed allows this switching to be done with shorter ray paths and fewer mirrors than with prior art. Without limiting the generality of the invention, the examples and embodiments described hereunder will be directed to switching optical waves in communications applications.

The task is mainly the production of tiny mirrors to use as switches in these arrays. Micro-machined devices are capable of fulfilling the task, provided that the micro-machining produces optical-grade mirrors in order to reduce losses. Actuation needs to be fast, simple, and allow reproducible and accurate alignment of the beam inputs and outputs as the mirrors bend the ray. In addition, the ability to deploy large arrays of mirrors is an essential feature of the system. All of these affect switching losses and utility. Previous art devices, although ingenious, were not able to achieve all of these requirements together. (See, for example: Toshiyoshi H. *et al.* "Electrostatic micro-torsion mirrors for an optical-switch matrix". *Journal of Microelectromechanical Systems*, vol. 5 No. 4, December 1996, page 231; and

Marxer C. *et al.* "Vertical mirrors fabricated by deep reactive ion etching for fiber-optic switching applications", *Journal of Microelectromechanical Systems*, vol. 6, No. 3, September 1997, page 277.)

A device that can separate a multi-wavelength beam into a bundle of parallel single wavelength rays and recombine them is also disclosed.

Usual fabrication methods are employed but enhanced mirror alignment and performance are achieved by fabricating mirrors on the surface of a wafer. A novel method is disclosed for fabricating 2D and 3D arrays, by bonding several laterally displaced wafers on top of one another.

According to the present invention there is provided an optical switch for switching a light ray including: (a) a substantially planar substrate having a portion that is transparent to the light ray; (b) a switching element having at least one reflective surface substantially parallel to the substrate; and (c) a mechanism for moving the switching element in a direction parallel to the substrate between (i) a first position wherein the light ray traverses the transparent portion of the substrate and (ii) a second position wherein the light ray is blocked from traversing the transparent portion of the substrate and reflected by the reflective surface.

According to one embodiment of the present invention the mechanism includes: (i) a first rigid element having two ends, the first end of the first rigid element being flexibly connected to a fixed point; (ii) a second rigid element having two ends, the second end of the first rigid element being flexibly connected to the first end of the second rigid element; and (iii) a tensile elastic element connecting the first end of the first rigid element to the second end of the second rigid element so that the distance between the first end and the second end when the elastic element is in a relaxed state is less than the sum of the distance between the ends of the first rigid element and the distance between the ends of the second rigid element; both the rigid elements being constrained to be movable only in a plane parallel to the substrate.

According to another embodiment of the present invention the mechanism includes: (i) a first element having two ends; (ii) a second element having two ends, the first end of the first element being flexibly connected to the first end of the second element; (iii) a third element having two ends, the second end of the second element being flexibly connected to the first end of the third element; (iv) a fourth element having two ends, the second end of the third element being flexibly connected to the first end of the fourth element; (v) two fixed anchor points, a second the end of the first element being flexibly connected to the first anchor point and the second end of the fourth element being flexibly connected to the second anchor point;

and (vi) a tensile elastic mechanism for maintaining the mechanism for moving the switching element in either of two stable states; all the elements being constrained to be movable only in a plane parallel to the substrate.

According to one embodiment of the present invention all the elements are rigid.

According to a further embodiment of the present invention the tensile elastic mechanism includes: (a) a tensile elastic element connecting the second end of the second element to the first anchor point so that the distance between the second end and the first anchor point when the elastic element is in a relaxed state is less than the sum of the distance between the ends of the first element and the distance between the ends of the second element: and (b) a tensile elastic element connecting the first end of the third element to the second anchor point so that the distance between the first end and the second anchor point when the elastic element is in a relaxed state is less than the sum of a distance between the ends of the third element and the distance between the ends of the fourth element.

According to another embodiment of the present invention the tensile elastic mechanism includes a tensile elastic element connecting the first end of the second element to the second end of the third element so that the distance between the first end and the second end when the elastic element is in a relaxed state is less than the sum of the distance between the ends of the second element and the distance between the ends of the third element.

According to another embodiment of the present invention the tensile elastic mechanism includes a spiral spring at each flexible connection.

According to another embodiment of the present invention the first element and the fourth element are elastic beams, the second element and the third element are rigid, the first element is rigidly connected to the first anchor point, and the fourth element is rigidly connected to the second anchor point

According to the present invention there is provided a hinge including: (a) a housing having a flat wall. (b) an element free to roll within the housing and having a connector that protrudes beyond the housing. (c) a mechanism for urging the rollable element against the wall as the element rolls within the housing so as to maintain rolling contact between the element and the wall.

According to one embodiment of the present invention the connector is rigid.

According to one embodiment of the present invention the urging mechanism is electrostatic.

According to another embodiment of the present invention the urging mechanism is magnetic.

According to another embodiment the present invention further includes (d) a restoring mechanism for returning the rollable element to contact with the wall in case of loss of contact.

According to one embodiment of the present invention the restoring mechanism includes: (a) two flexible cables: (i) the first end of the first cable being operationally connected to but electrically insulated from the housing, (ii) the first end of the second cable being operationally connected to but electrically insulated from the housing, (iii) the second end of the first cable being operationally connected to but electrically insulated from the rollable element, and (iv) the second end of the second cable being operationally connected to but electrically insulated from the rollable element; (b) two electrodes for resetting the rollable element in place: (i) a first the electrode being situated opposite the first cable on a side away from the rollable element, and (ii) the second electrode being situated opposite the second cable on a side away from the rollable element, (c) a mechanism for charging the electrodes; and (d) a mechanism for charging the cables.

According to one embodiment of the present invention, in the restoring mechanism (a) the cables are slack while the rollable element is in contact with the wall, and (b) at least one cable is taut when the rollable element loses contact with the wall.

According to the present invention there is provided a travelling wave actuator for moving an object including (a) an elastic membrane, (b) a mechanism for maintaining contact between the object and the membrane, and (c) a mechanism for generating a travelling wave in the membrane.

According to one embodiment of the present invention the travelling wave actuator further includes (d) a substrate whereupon the elastic membrane is deposited.

According to one embodiment of the present invention the mechanism for maintaining contact is electrostatic.

According to another embodiment of the present invention the mechanism for maintaining contact is magnetic.

According to one embodiment of the present invention the mechanism for generating a travelling wave includes: (i) a plurality of electrode pairs, equally spaced along and

straddling the membrane. and (ii) for each pair. a respective alternating electrical power supply.

According to another embodiment of the present invention the mechanism for generating a travelling wave is magnetic.

According to another embodiment of the present invention the mechanism for generating a travelling wave is thermal.

According to another embodiment of the present invention the mechanism for generating a travelling wave is piezoelectric.

According to the present invention there is provided an actuator for moving an element comprising: (a) a stationary support for the element. (b) a deflectable support for the element operative to: (i) raise the element from the stationary support. (ii) advance the element in a required direction of motion. (iii) deposit the element upon the stationary support. and (iv) return to a starting position thereof.

According to one embodiment of the present invention (a) the stationary support includes a cluster of fingers. the cluster being sufficient to support the element. and (b) the deflectable movable support includes at least one cluster of fingers. each cluster being sufficient to support the element.

According to a further embodiment of the present invention each finger includes a surface at a tip thereof. whereupon the element is supportable.

According to a further embodiment of the present invention the element is a planar switching element.

According to a further embodiment of the present invention the deflectable support is activated electrostatically.

According to a further embodiment of the present invention the deflectable support is activated piezoelectrically.

According to the present invention there is provided an emergency holding device for a movable switching element including: (a) a buckled beam having: (i) a first stable configuration concave towards the switching element. and (ii) a second. tense configuration. concave towards the switching element. wherefrom. if relieved. the beam relaxes to the first stable configuration: and (b) a flexible strap straddling the switching element. the strap being:

(i) attached at a first end thereof to a center of the beam and perpendicular thereto, and (ii) anchored at a second end thereof at a fixed point, so that, at the concave stable configuration, the strap constrains the switching element.

According to one embodiment of the present invention the flexible strap is electrically conductive, the device further comprising: (c) an electrode placed opposite the strap.

According to the present invention there is provided a mechanism for lateral realignment of a free movable element with respect to a rectilinear motion path thereof comprising: (a) two alignment pads on opposite sides of the element, (b) a mechanism for bringing the pads into contact with the movable element, thereby nudging the element to the laterally aligned position, and (c) a mechanism for retracting the pads from contact.

According to one embodiment of the present invention each the alignment pad includes an electrode.

According to one embodiment of the present invention the contact mechanism is elastic.

According to another embodiment of the present invention the contact mechanism is electrostatic.

According to another embodiment of the present invention the realignment mechanism further includes: (d) two walls situated on opposite sides of the movable element and outside the alignment pads, and (e) elastic elements attaching each alignment pad to the nearer wall.

According to another embodiment of the present invention the realignment mechanism further includes: (d) two walls situated on opposite sides of the movable element and outside the alignment pads, each wall including an electrode, and (e) elastic elements attaching each alignment pad to the nearer side of the movable element.

According to one embodiment of the present invention the retracting mechanism is electrostatic.

According to another embodiment of the present invention the retracting mechanism is magnetic.

According to the present invention there is provided a mechanism for continuous lateral realignment of a free movable element with respect to a motion path thereof including: (a) a stationary electrode adjacent to and clear of the path, (b) a second, movable electrode: (i) attached to the element, (ii) at least partially overlapping the stationary electrode, and (iii)

constrained to remain parallel to the stationary electrode so that a gap remains therebetween. and (c) a mechanism for electrostatically charging the electrodes. the resulting electrostatic force between the electrodes acting to maintain the element in the motion path.

According to one embodiment of the present invention the motion path is confined to a plane.

According to another embodiment of the present invention the motion path is rectilinear.

According to a further embodiment of the present invention the realignment mechanism. includes: (d) a second stationary electrode adjacent to and clear of the path, (i) lying in a same plane as and clear of the first stationary electrode, (ii) opposed to the first stationary electrode with respect to the motion path. and (iii) at least partially overlapped by the movable electrode so that a gap remains therebetween. and (e) a mechanism for electrostatically charging the second stationary electrode. the resulting electrostatic force between the electrodes acting to maintain the element in the motion path.

According to a further embodiment of the present invention the stationary electrodes are shaped as mutual mirror images and are symmetrically disposed about the path.

According to a further embodiment of the present invention the charge on the second stationary electrode is of same polarity as the charge on the first stationary electrode.

According to a further embodiment of the present invention the charge on the movable electrode has the same polarity as the charge on the stationary electrodes.

According to another embodiment of the present invention the charge on the movable electrode is of opposite polarity to the charge on the stationary electrodes.

According to a further embodiment of the present invention the shape of each electrode is an isosceles triangle, an axis of symmetry whereof is oriented perpendicular to the motion path.

According to the present invention there is provided a method of moving an object including the steps of: (a) urging the object to be in contact with an elastic membrane while (b) generating a traveling wave in the membrane.

According to the present invention there is provided a method of moving an element including the steps of: (a) providing: (i) a stationary support for the element. and (ii) a deflectable support for the element. and (b) cyclically operating the deflectable support to: (i) raise the element from the stationary support. (ii) advance the element in a required direction

of motion. (iii) deposit the element upon the stationary support. and (iv) return to a starting position thereof.

According to the present invention there is provided a method of holding an electrostatically supported switching element in the event of cessation of a supply of power to the switching element. including the steps of: (a) providing a flexible strap straddling the switching element. and having a first configuration wherein the strap constrains the switching element and a second configuration wherein the switching element is free from the constraint: and (b) maintaining the strap in the second configuration only while power is supplied.

According to the present invention there is provided a method of laterally realigning a free movable element in a direction perpendicular to a rectilinear motion path thereof including the steps of: (a) providing a realignment mechanism including two movable alignment pads on opposite sides of the element. (b) bringing the pads into contact with the movable element. thereby nudging the element to the rectilinear motion path. and (c) retracting the pads.

According to the present invention there is provided a method of continuously laterally realigning a free movable element with respect to a motion path thereof comprising the steps of: (a) providing: (i) a stationary electrode adjacent to and clear of the path. (ii) a second. movable electrode attached to the element. at least partially overlapping the stationary electrode. and constrained to remain parallel to the stationary electrode so that a gap remains therebetween. and: (iii) a mechanism for electrostatically charging the electrodes. and (b) electrostatically charging the electrodes.

According to one embodiment of the present invention the method includes the further steps of: (c) providing: (i) a second stationary electrode adjacent to and clear of the path. lying in a same plane as and clear of first the stationary electrode, opposed to the first stationary electrode with respect to the motion path. and at least partially overlapped by the movable electrode so that a gap remains therebetween. and (ii) a mechanism for electrostatically charging the second stationary electrode.

According to a further embodiment of the present invention the method includes the further step of providing that the stationary electrodes are shaped as mutual mirror images and are symmetrically disposed about the path.

According to a further embodiment of the present invention the method includes the further step of charging the second stationary electrode with a polarity the same as the charge on the first stationary electrode.

According to a further embodiment of the present invention the method includes the further step of charging the movable electrode with a polarity the same as the charge on the stationary electrodes.

According to another embodiment of the present invention the method includes the further step of charging the movable electrode with a polarity opposite to the charge on the stationary electrodes.

According to another embodiment of the present invention the method includes the further step of providing that the stationary electrodes are shaped as isosceles triangles.

According to the present invention there is provided a method of fabricating a micro-device having a high-quality smooth mirror surface comprising the steps of: (a) polishing a substrate surface to a required smoothness. (b) depositing mirror material on the substrate. and (c) removing a superfluous part of the substrate adjacent to a surface of the mirror.

According to the present invention there is provided a method of fabricating a micro-device having a high-quality smooth mirror surface comprising the steps of: (a) depositing a sacrificial layer on the substrate. (b) polishing a surface of the sacrificial layer to a required smoothness, (c) patterning the sacrificial layer to provide for auxiliary elements. (d) depositing mirror material on the polished surface of the sacrificial layer. (e) depositing the auxiliary elements on the patterned portion of the sacrificial layer. and (f) removing the sacrificial layer.

According to another embodiment of the present invention the method further includes the step of: (g) removing a superfluous part of the substrate.

According to the present invention there is provided a method of fabricating an envelope-actuated micro-device having a high-quality smooth mirror surface including the steps of: (a) providing a first substrate. (b) depositing an electrode on the first substrate. (c) depositing a first sacrificial layer on the electrode and the first substrate. (d) polishing a surface of the first sacrificial layer to a required smoothness. (e) patterning the first sacrificial layer to provide for a first set of auxiliary elements. (f) depositing mirror material on the polished surface of the first sacrificial layer. and (g) depositing the auxiliary elements on the patterned portion of the first sacrificial layer.

According to another embodiment of the present invention the method includes the further step of: (h) providing a second electrode.

According to another embodiment of the present invention the method of providing the second electrode is effected by the further steps of: (i) depositing a second sacrificial layer on the mirror material. (ii) patterning the second sacrificial layer to provide for the second electrode and a second set of auxiliary elements. and (iii) depositing the second electrode and the second set of auxiliary elements on the patterned portion of the second sacrificial layer.

According to another embodiment of the present invention the method of providing the second electrode is effected by the further steps of: (i) providing a second substrate, (ii) depositing the second electrode on the second substrate, (iii) aligning the second electrode opposite the micro-device as fabricated on the first substrate, and (iv) bonding the second substrate to the first substrate.

According to another embodiment of the present invention the method includes the further step of: (h) removing the first sacrificial layer.

According to another embodiment of the present invention the method includes the further step of: (h) removing a superfluous part of the substrate.

According to the present invention there is provided a mechanism for providing a strictly non-blocking switching configuration comprising two coupled substantially identical tri-cube complex switching arrays: (a) each capable of switching any input element to any output element, (b) the first array being capable of allowing any input element to transit unswitched to a corresponding input of the second array, and (c) the second array being capable of allowing any output element from the first array to transit unswitched to a corresponding output of the second array.

According to the present invention there is provided a method of strictly non-blocking switching including the steps of (a) providing two coupled substantially identical tri-cube complex switching arrays: (i) each capable of switching any input element to any output element, (ii) the first array being capable of allowing any input element to transit unswitched to a corresponding input of the second array, and (iii) the second array being capable of allowing any output element from the first array to transit unswitched to a corresponding output of the second array, and (b) operating the switching arrays coupled in parallel.

Brief Description of the Drawings

The invention is herein described, by way of example only, with reference to the accompanying drawings, wherein:

Figure 1 shows the general switch layout and basic switching motions;

Figure 2 shows switch zones;

Figure 3 shows basic switching actions;

Figure 4 illustrates how a switch can direct two parallel inputs to separate outlets, by operating a switching element entirely within an optically active zone;

Figure 5 shows the principles of envelope actuation of a switching element;

Figure 6 presents two different designs for curved-beam actuation;

Figure 7 illustrates the use of magnetic actuation;

Figure 8 shows various bistable beam supports;

Figure 9 shows further examples of bistable beam supports;

Figure 10 presents a representation of the use of bistable beams with a micro-mechanical switching element;

Figure 11 illustrates the action of a frictionless joint;

Figure 12 presents a more complex application of a frictionless joint;

Figure 13 shows a resetting mechanism in the event of power failure;

Figure 14 illustrates travelling-wave actuation;

Figure 15 shows the mechanism of finger actuation;

Figure 16 shows a variation on finger actuation

Figure 17 presents a mechanism for securing a movable element in the event of power failure;

Figure 18 illustrates an electro-mechanical method of aligning a movable element;

Figure 19 shows a variant of the method of figure 18;

Figure 20 shows how electrostatic forces can maintain alignment;

Figure 21 presents applications of electrostatic alignment;

Figure 22 shows some basic switching actions with two crossed rays;

Figure 23 presents a two variations of a basic 2D switch array;

Figure 24 shows a schematic view of multi-layer switch array;

Figures 25 illustrate 3D switching methods involving two or more multi-layer switch arrays, including a partially blocking configuration, a Clos architecture (non-blocking) configuration, and a strictly-non-blocking configuration;

Figure 26 shows a wavelength-separation/recombiner device;

Figure 27 illustrates basic switch fabrication processes;

Figure 28 shows fabrication stages of a 3D switch array; and

Figure 29 shows an isometric view of a 3D array cube.

Description of the Preferred Embodiments

Introduction

The wave valve of the present invention is intended to be used in fiber-optic communications to overcome the above-mentioned shortcomings of previous art. although other applications can be envisioned. It employs mirrors to perform the switching. Mirrors have the advantage of being substantially insensitive to wavelength. The active environment is air. some other gas, or a vacuum. This is a non-blocking environment: i.e. it allows rays to cross unimpeded. Thus there is no cross-talk and almost no attenuation by the medium. Most losses occur during light transfer from and into the fiber at the switch/fiber interfaces. Losses also arise from beam spreading. but use of collimating lenses and short distances can reduce these.

The mirrors should be small. to allow fast response and compactness. The mirrors are generally micro-machined and. in order to reduce losses. are designed to be of optical grade. Actuation should provide reproducible and accurate alignment of the beam inputs and outputs while the mirror bends the ray. In addition. the ability to form large arrays is an essential requirement of the system. All these requirements reflect on switch loss and utility. Prior art devices, although ingenious. were not able to fulfil all these requirements together [Toshiyoshi H. et al.. "Electrostatic micro torsion mirrors for an optical switch matrix". *Journal of Microelectromechanical Systems*. vol. 5 No. 4 page 231. December 1996. and Marxer C. et al. "Vertical mirrors fabricated by deep reactive ion etching for fiber optic switching applications". vol. 6 No. 3 page 277. September 1997].

These factors are incorporated into the design of the valve. which is generally planar and fabricated on a smooth wafer substrate. unlike prior art wherein the mirrors are etched into the wafer bulk. In order to enhance switching speed. the mirror moves parallel to the substrate, thereby reducing air resistance and minimizing small deviations of the mirror from the normal (90°) to the substrate that account for part of the losses introduced in prior art systems. Moreover. the principles presented here are designed to give higher actuating forces, thus allowing a faster response than in prior art switches.

Single valve configuration and operation.

Referring to Figure 1a and 1b. the valve consists of a flat mirror 1 situated above. on, inside. or below. and parallel to a substrate 2. In the figure. it is shown at a short distance *d* from the

substrate. Mirror 1 may move to different positions in a plane 3 parallel to a surface of substrate 2, either substantially curvilinearly, as in a pendulum-like motion 5 in Figure 1c, or in a substantially rectilinear motion in any direction, such as 6 or 6A in Figure 1d, or in some combination of these. In a preferred embodiment, motion is generally parallel or normal to a base line 7 (Figure 2), that separates an opaque zone 8 of substrate 2, wherethrough light 10 cannot pass, from a transparent zone 9, wherethrough light 10 can pass and wherein switching takes place. Zone 9 may be transparent because the material of substrate 2, which is present in zone 8, is absent in zone 9, or because the material of substrate 2 in zone 9 is transparent to a relevant wavelength. Different embodiments of the principles disclosed here can be devised by those skilled in the art, wherein it is possible to distinguish the zones in other ways.

One approach is illustrated in Figure 3. Mirror element 1 is located opposite an opaque zone 38 of substrate 2 while light 10 transits unobstructed through a transparent zone 39. In this condition, the system is in an OFF state 1A, as shown in Figure 3a, b. Mirror 1 is movable rectilinearly, parallel to substrate 2, to a position opposite zone 39, as shown by double-headed arrow 36, to an ON state 1B (Figure 3c, d). While mirror 1 is in OFF state 1A, light 10 can pass from one side 39A of surface 3 to another side 39B.

In a preferred embodiment (Figure 3e, f) ray 10 is inclined at 45° to mirror 1. In OFF state 1A, ray 10 transits transparent zone 39 unimpeded from 10A to 10B. When mirror 1 is in ON state 1B, ray 10 is reflected along an alternate path 10C. Thus ray 10 has one input state 10A and two possible, mutually exclusive, output states 10B and 10C.

In another embodiment (Figure 4), mirror 1 is movable along a line of motion 46 which lies entirely opposite a transparent part 49 of plane 3 and, by so doing, simultaneously exchanges blocking and non-blocking states in different parts of zone 49. Mirror suspension and actuation elements are placed opposite another, opaque zone 48 of plane 3. As previously explained, in a non-blocking state 41A (Figure 4c), light from 10A passes to exit 10B while, in blocking state 41B, light is reflected to an alternate output 10C. In this configuration, where mirror 1 is entirely opposite transparent zone 49, either position of mirror 1 can be designated as ON or OFF (Figure 4e, f). Thus, it is possible to have a valve with two parallel inputs 10 IA and 10 IIA being in an ON state for the former, reflecting ray 10 IA to output 10 IC, while being in an OFF state for the latter, which passes to output 10 IIB (Figure 4e). On actuating switch 1, these states reverse and input ray 10 IA is in an OFF state, transiting to

output 10 IB, while input ray 10 IIA is in an ON state, reflecting to output 10 IIC. This makes a (1×2)×2 exchange switch, which may be used, for example, in a Banyan network.

More elaborate applications can be realized by combining two or more switching elements. It is important to note that the rays can traverse the switch in a reverse direction. In this case, inputs interchange with outputs and the switching options explained above are reversed.

Actuation

The valve consists of mirror 1 which is movable parallel to surface 3 and may be in at least two rest positions. Mirror 1 reflects light at one position and allows its passage at another position. Any appropriate force may be applied to induce a desired change in mirror position. A number of actuation methods are available: thermal (bimetallic strips), magnetic, piezoelectric, mechanical, and electrostatic actuation and methods that rely on shape memory alloys (SMA) are a few of many known in the art.

Three preferred actuation embodiments are discussed. The first follows a design similar to a comb-drive but designed to produce larger forces than prior-art implementations. It uses an envelope-like electrode into which a mirror is retracted. Larger forces can be obtained with this actuation method by designing the electrode edges to have a large area change, such as a fractal form.

Alternatively, a mirror is supported by flexible beams that are actuated by attraction to or repulsion from static, curved electrodes.

Magnetic actuation is also described whereby a magnetic field is established around a switch and a flowing current induces switching.

Electrostatic envelope actuation

A preferred embodiment employs electrostatic actuation. Different schemes of electrostatic actuation can be used, among them a comb-drive mechanism. (Hirano T. *et al*, "Design, Fabrication, and operation of submicron-gap comb-drive microactuators", *Journal of Microelectromechanical Systems*, vol. 1 No. 1, March 1992, page 52.) In conventional comb-drive actuation, the actuation force depends on the change of the overlapping area between a driver's fingers and a comb. Since usual fabrication methods limit that area to a small value, a large number of fingers is necessary to produce the required force. Therefore

this kind of actuation requires large actuators. A different approach to this actuation principle is disclosed here (Figure 5).

Overlapping finger 51 and comb 52 form a capacitor (Figure 5b). The attractive force between the movable and static fingers is:

$$F = -\frac{\partial U}{\partial x}$$

where

$$U = \tfrac{1}{2} C V^2$$

is the electrical energy stored in the capacitor of capacitance C. The capacitance of a parallel-plate capacitor is determined by the geometric parameters thereof and depends directly on the area (A) and inversely on the gap between the electrodes (g_0). In the case considered here:

$$C = \varepsilon_0 \frac{A}{g_0} = \varepsilon_0 \frac{h_0 x}{g_0}.$$

The force is, therefore:

$$F = -\frac{\varepsilon_0 V^2 h_0}{2 g_0}.$$

Where, ε_0 is the permittivity of the vácuum, V an electrical potential, h_0 is width of the finger, x is the overlapping length of the finger in the direction of advance thereof, and g_0 is the gap between the movable finger and each static finger. Thus the force is inversely proportional to the gap between the fingers and proportional to the width of the fingers. It does not depend on the thickness of or the amount of overlap between movable and static fingers. Based on this conclusion, a configuration is disclosed wherein the width of the finger is increased in order to achieve greater force and thus faster switching speed..

The production of wide fingers is difficult with conventional, prior art. A fabrication technique is disclosed below wherein the manufacture of wider fingers is easily done using conventional methods. In this way, fewer fingers, or even a single finger, can achieve sufficient force and hence switching times of the order of microseconds, compared to milli-seconds with prior art. The disclosed actuator has an envelope-like configuration in which mirror / finger (movable electrode) 51 may enter or exit envelope (static actuating electrode) 52.

In another embodiment (Figure 5d), at least two actuating electrodes are placed in a way that one set **52A** actuates to an ON position while another set **52B**. **C** actuates to an OFF position. Actuation can be made bistable: if the actuated mirror is supported by buckled beams (see below), a snap action to each position of the mirror results.

Another possible embodiment to implement bistability employs electrostatic snap (pull-in) action. An actuated element is attracted to and held by an electrically isolated electrode at an end of its motion. From the equations above, force exerted is given by:

$$F = -\frac{\varepsilon_0 V^2}{2g_0}\frac{\partial A}{\partial x}.$$

Since force depends on the change of area A with displacement x, then, to increase the force, the area change of this actuator should be increased, not only the width of the finger. Therefore, for the actuator presented, the force can be increased further by using a more complex profile than a straight line (**57**, Figure 5c) that the electrode crosses, thereby increasing the rate of area change. This line can be designed, for example, to be circular (**57B**, Figure 5e), and the force increases correspondingly. Alternatively, or additionally, the leading edge of electrode **51** may be similarly enlarged.

Another embodiment increases the profile by using an even more complex geometrical form. Such a form might be an irregular form such as a fractal line designed for the application. The use of a fractal form can increase the actuating force by the ratio of its rate of area change to that of a straight-line profile.

Curved electrode actuation

Another electrostatic actuation method is presented in Figure 6, in which the post-fix **A** or **B** refers respectively to variant embodiments. One or more flexible beams **67A** or **67B** support a mirror **61**. One point of the beam(s) **68A** or **68B** is fixed in close proximity to a circular segment stator **69A** or **69B** attached to a substrate **62**. These stators and beams are conductive and respectively chargeable with opposite polarity. Beam **67A** or **67B** and stator **69A** or **69B**, respectively, are separated by insulators **65A** or **65B** from each other along an entire circular segment of stator **69A** or **69B** or, at least, at points where contact may otherwise occur, so as to prevent a short circuit (Figure 6a, b, c, and d).

Applying a potential difference between stator **69A (B)** and movable beam **67A (B)** sets charges of opposite polarities on stator **69A (B)** and beam **67A (B)**, so that the latter is attracted to the former, as close as permitted by the insulation (Figure 6b, 6d). Removing the

potential difference allows beam **67A (B)** to return to the original shape thereof. Since a free end of beam **67A (B)** is connected to mirror **61**, the consequent advance or retreat of the contact zone around a perimeter of stator **69A (B)** moves mirror **61A (B)** a distance **L** in a direction indicated by double-headed arrows **66A (B)**. This method is especially useful when actuating elements **67A (B)**, **68A (B)**, and **69A (B)** are completely within substrate **62A (B)** with mirror **61** being entirely opposite transparent zone **63**, as described previously. It is an alternative where envelope-type actuation is not preferred. Buckled beams are used so that actuation is inherently bistable. In order to move mirror **61** a distance **L**, the height of stator **69A (B)** is preferably approximately **L**. If stator **69B** is a quadrant of a circle, the height should approximate the circle radius and have a value of **L**.

Another embodiment of this actuation method (Figure 6e, f) employs opposed-quadrant stators. In this case pairs of quadrant-shaped stators **69C** are separated by a beam **67C** so that beam **67C** is tangential to both quadrants at a point of contact and both quadrants are relatively opposed so that a radial boundary of each quadrant forms a straight line passing through that point of contact. As before, both stators are prevented from contacting beam **67C** by insulating material **65C**. In this configuration, by use of opposite charges on each member of a stator pair, half of the motion is caused by one member and the other half by the other member, in sequence. This allows a more compact actuator to be constructed.

Magnetic actuation

Another embodiment of the valve switch uses magnetic forces. Magnetic fields can produce greater forces and, consequently, faster switching. A disadvantage is the larger overall volume of the device, even though the switching mechanism, itself, has the same dimensions whatever the actuation mechanism. In order to use this actuation method (Figure 7), a magnetic field, **B**, is necessary at the switch. The field can be produced by conducting loops around each switch, by a permanent magnet, or by an electromagnet with similar field. These are only some of the available magnetic field application possibilities.

In this embodiment of the switch, mirror **71** is supported by beams, **77A** and **77B**. These beams are preferably made from buckled beams, to produce bistable operation, and are conductive or include a conducting layer wherethrough an electric current **I** may be passed. Interaction with the magnetic field induces a lateral force **F** on the beams. The magnetic field is aligned so that current **I** actuates mirror **71** to a new position (Figure 7a). Reversing current **I** reverses force **F** and returns mirror **71** to an original position (Figure 7b). Higher field values or higher currents produce stronger forces and faster switching.

Bistable support

Realization of the aforementioned systems requires a means of supporting active elements that enables bistable operation. The devices described hereunder relate to the present invention but may also be used in other applications. for example in conveyor systems. Translation systems that variously include a frictionless hinge. surface-wave motion. and beams that vibrate in two directions are described. Different actuation methods, including electrostatic or magnetic actuation against elastic restraints or buckled beams, are utilized in order to lock a translated mirror in a newly attained position. A buckled beam is used as a mechanical memory element. a task it can fulfill if the length of the beam is larger than the distance between the anchor points thereof. By applying a force normal to the length of a buckled beam a critical point is reached whereupon the beam transits to another stable configuration. The same effect is also possible if the beam takes other forms. which are also described.

In Figure 7. each buckled beam, **77A** and **77B**, is a variation of a bistable buckled element with a bistable, snap mechanical action. The basic principle of the buckled beam is shown in Figure 8a. A beam **80** has intrinsic elasticity and its length is greater than a distance between anchor points **81** and **82**. If a lateral force **F** be applied to beam **80**. as known from standard texts. the beam snaps from a stable state **80** to another stable state **80'**. Applications of this principle are illustrated in Figures 8b. c. and d. in which like reference numerals refer to like parts throughout the figures of the drawing. It is to be understood that the descriptions below are illustrative. and are not intended to restrict the present invention to the specific details set forth below.

The device of Figure 8b is bistable. analogous to the buckled beam. and the components are correspondingly numbered. The beam includes rigid elements. **80A** and **80B** flexibly connected at respective ends **$80A_1$** and **$80B_1$**. Element **80A** is flexibly connected at end **$80A_2$** to fixed anchor point **82** while element **80B** is unanchored at end **$80B_2$**. Ends **$80A_2$** and **$80B_2$** are connected by a tensile element represented by a spring **83**, although it is obvious that other ways may achieve substantially the same effect. such as using spiral springs at connections **$80A_1$ – $80B_1$** and **$80A_2$ – 82**, or some other combination easily devised by those skilled in the art. A second stable configuration of this element is represented by the dashed lines denoted by **80A'** and **80B'**. This device, like that in Figure 8a, may be regarded as an elementary. bistable building block.

A snap element that has two static configurations is shown in Figure 8c. Rigid elements **80A** and **80B** are flexibly connected at ends **80A$_1$** and **80B$_1$** respectively; **80B** and **80C** are flexibly connected at ends **80B$_2$** and **80C$_2$** respectively, at a point **84**; and **80C** and **80D** are flexibly connected at ends **80C$_1$** and **80D$_1$** respectively. There are two anchor points, **82** and **82A**, whereto are flexibly connected ends **80A$_2$** and **80D$_2$** respectively. A tensile element, represented by a spring **83A**, connects anchor point **82** to the flexible connection between ends **80B$_2$** and **80C$_2$** and another tensile element, represented by a spring **83B**, connects anchor point **82A** to the flexible connection between ends **80B$_2$** and **80C$_2$**. The whole device is constrained to move within a plane. Applying force **F** snaps the device to a new stable position, the distance between points **82** and **82A** remaining constant while point **84** moves to a new location **84'**, as shown schematically in Figure 8d.

To show the generality of the design another preferred embodiment is shown in Figures 9a and 9b, where elasticity is provided by a spring **90**. In this embodiment, force **F** produces snap action to bring point **84** to a new stable position, **84'**. Figure 9c shows an equivalent embodiment wherein elasticity is provided by spiral springs **92A, B, C, D, E,** and **F**. Another embodiment employs an elastic beam as part or all of the elastic members of the device to produce the elasticity, as shown in Figure 9d. In this embodiment, anchor points **82** and **82A** rigidly hold fully or partially elastic members **80A** and **80D** at ends **80A$_2$** and **80D$_2$** respectively. All other members remain as in the previous example. Figure 9e shows a partially actuated state of this embodiment, showing elastic members **80A** and **80D** bent, allowing the transit of point **84** to a new stable state, as before.

To make the device useful, joint **84**, or any other point or beam in the device, is attached to something that one wishes to move. In one preferred embodiment joint **84**, can be replaced with or attached to a usable element, such as a mirror, as shown in Figure 10, which depicts a double application of the arrangement in Figure 9c and is labeled to show corresponding components, the duplicate part of the mechanism being labeled with primed numbers. In this figure, **84** represents a usable element. Another possible application is as a switch in which different connections are made in each state of the bistable device.

Frictionless joints

In micromechanical applications, frictionless hinges are advantageous. Dynamic friction is normally a cause of wear, suppression of which is especially important for micromachines, where lubricants are not generally usable. For this reason, pin joints are usually replaced by

spiral springs where large movement is required. Another type of hinge is presented which uses static friction but is dynamically frictionless.

The hinge in Figure 11 includes a cylindrical roller **111** from which protrudes a radial arm **112**, the movable element thus formed being in contact with a surface **114** contained within a housing **113**. Arm **112** protrudes out of housing **113**. Large static friction between roller **111** and surface **114** as **111** rolls on **114** means that no slippage occurs during the rolling. This requires that contact be maintained at all times between roller **111** and surface **114**: this is termed "rolling contact" and is achieved by the action of a normal force **F** urging contact between roller **111** and surface **114**. Force **F** may include electrostatic and magnetic forces. Through rolling contact, roller **111** may move between position **111A** and position **111B** and, consequently, arm **112** moves between position **112A** and position **112B**. The whole arrangement forms a dynamically frictionless hinge with center of rotation at a point **115**, which is not the center of roller **111**, and with an angular range 2α.

This hinge can be employed more than once in an implementation, as illustrated in Figure 12. Here, the result enables translation of a movable part **122** relative to a stationary housing **113** in directions **127+** and **127-**. As before, in order for the hinge to function, a normal force is needed to maintain contact between rotor **112** and housing **113** and between rotor **112** and movable part **122**, which rotor **112** connects. Again, different types of force may be used, including magnetic and electrostatic forces. In case of a magnetic force, movable part **122** and stationary housing 113 of the hinge include permanent magnets or electromagnets. If electrostatic attraction be employed, a thin insulating layer **123** is deposited to cover at least all of the possible contact surfaces of the hinge so as to prevent a short circuit, as shown in Figure 12. An electrostatic potential is applied between rotor **112** and embedded electrodes **125a** and **125b**. The potential is provided by direct connection of the electrodes to a power supply or through electrostatic induction, electrodes 125a and 125b being oppositely charged. The potential difference induces attractive normal forces between rotor **112** and embedded electrodes **125a** in housing 113 and **125b** in movable part 122. The same consideration applies if more than one hinge exists, in which case electrostatic attraction may be more suitable than magnetic attraction. Charges may also be applied to stoppers **126a** and **126b** of the hinge, by means of embedded electrodes **128a** and **128b**, in order to produce electrostatic forces to actuate rotor 112, which may then be used either to actuate an element or to act as a control device by, for example, detection of capacitance change caused by the induced motion thereof to provide positional information.

If a device relies on electrostatic attraction, cessation of the power supply may allow a rotor to fall from a working position. In order to restore to the working position, a mechanism, as shown in Figure 13a is used as one of the options. Figure 13 shows views of the device of Figure 11 from within the plane of Figure 11, and relevant parts are similarly numbered. Part of a housing **113** in contact with a rotor **111** is viewed schematically from the plane of motion of protruding part **112**. While power is supplied, both elements are in contact but for a separating, insulating layer **123**, as described before. Flexible, loose conductive cables **131A** and **131B** are anchored to either side of housing **113**. In Figure 13a, masts **130A** and **130B**, emerging from either side of housing **113**, are used to illustrate this. Masts **130A** and **130B** also electrically insulate cables **131A** and **131B** from housing **113**. Insulation 133 may be also provided for cables **131A** and **131B** from rotor **111** as is also a means **134A** and **134B** of electrically charging the cables. Resetting electrodes **132A** and **132B** are situated to the sides of the hinge, outside cables **131A** and **131B** and provided with respective means **135A** and **135B** of being electrostatically charged. In normal operation, cables **131A** and **131B** are relaxed. When power fails, the attraction between rotor **111** and housing **113** ceases and rotor **111** falls until checked by one taut cable, in this case **131A**, while other cable **131B** remains slack, as shown in Figure 13b. When power is restored, a resetting procedure is followed to restore the hinge: first, a voltage **135A** is applied to electrode **132A** and an opposite voltage **134A** to cable **131A** so that electrode **132A** attracts cable **131A**. Simultaneously, a voltage **135B** is applied to electrode **132B** and an opposite voltage **134B** to cable **131B** so that electrode **132B** attracts cable **131B**. The resultant tensing of cables **131A** and **131B** returns rotor **111** to a working position, as shown in Figure 13c. Then the electrostatic attraction between housing **113** and rotor **111** is renewed and the two elements will remain together. Finally, power supply to resetting electrodes **132** and cables **131** is ceased, leaving cables **131** slack. Operation of the hinge can then be resumed.

Other applications and realizations of the described mechanism can be envisioned by those skilled in the art.

Travelling-wave actuation

Another method of actuation is now introduced. In Figure 14, a standing wave **140** is induced in an elastic material **141** situated on a substrate **142** by any method that can cause a modification of the dimensions of elastic membrane **141**. The modification method, which may affect the time constant of standing wave **140**, may be thermal, piezoelectric, magnetic, or electrostatic. In a preferred embodiment, electrostatic actuation is used. An oscillating

voltage 144 is applied across a pair of electrodes 143 placed in substrate 142 and above elastic material 141, causing vibration of elastic membrane 141. Alternating voltage 144 induces a standing wave 140 in elastic membrane 141. If two pairs of electrodes 143A and 143B be laterally separated with their respective cycles 144A and 144B having the right phase difference, as in Figure 14b, a traveling wave 145 is produced at a surface of elastic medium 141: a point on elastic material 141 will undergo circular motion 146 (Figure 11c). This circular, wave-like motion can move an element 148 placed on top of elastic material 141. Changing the phase difference between electrodes 143A and 143B, and thus between the standing waves, can change the velocity and direction of traveling wave 145 and, with it, the velocity and direction of element 148 placed on elastic membrane 141. A plurality of electrodes and generating devices may be used as required. Although such waves are known from prior art this device is innovative, as described in the following.

The functioning of this device requires contact and friction between movable element 148 and elastic membrane 141, in which waves 145 propagate. In prior art, that contact is maintained by virtue of gravity or by springs. The current invention, being intended for elements of small dimensions, introduces other options, including magnetic force and electrostatic force.

For the former, movable element 148 is made of magnetic material, as are the surrounding parts of elastic membrane 141 or substrate 142. By oppositely magnetizing 148 and 141 and/or 142, an attractive normal force holds movable element 148 against elastic membrane 141, even against gravity, and induces friction that will permit the functioning of the device. Either permanent magnets or electromagnets may be used. Another possibility is electrostatic attraction between movable element 148 and the stationary part of the device. Again, the attraction produces a force that induces the static friction that enables the actuator to function. This enhancement permits the functioning of the device in any orientation, without relying on gravity or springs or other elements that may produce dynamic friction and wear or require the use of bearings that are difficult to fabricate at micro-dimensions. The use of this kind of actuator in the optical cross-connect, the aforementioned mirror and movable part, is an innovative improvement.

In case magnetic actuation is preferred, the electromagnetic attraction of the previous paragraph is caused to vary cyclically so as to induce a required travelling wave in the membrane.

In case thermal actuation is preferred, the membrane is selectively heated by heater 149 in Figure 14(d) to cause periodic deformation so as to induce a required travelling wave in the membrane.

In case piezoelectric actuation is preferred, piezoelectrically deformable device **149** in Figure 14(d) is caused to change dimensions in contact with the membrane to cause periodic selective deformation therein so as to induce a required travelling wave in the membrane.

Finger actuation

Although the surface wave device is usable in some cases, a more versatile device can be designed. The intention is to produce a rotational motion at the movable element that resembles that of **146** in Figure 14, without actually needing to propagate a surface wave.

The design (Figure 15a) is based on clusters of supporting fingers **153**, each cluster being sufficient to support a movable element **152**. Fingers **153** can have various configurations, such as cantilevers protruding from a side wall or posts protruding from a substrate **151**. Although the illustration shows the finger tips aligned in a straight line, this is not an essential requirement of the invention. Movable element **152** rests on supporting fingers **153**. An appropriate movable element **152** for this application is an actuatable mirror. The supporting surfaces of fingers **153** are generally located above the plane of substrate **151**. A working cycle is illustrated in Figures 15b – 15e and starts when a first cluster of supporting fingers **153B, D** moves away from substrate **151** bearing movable element **152**. At this stage, a second cluster of supporting fingers **153A, C** is stationary and thus out of contact with movable element **152**. Next, first cluster of supporting fingers **153B, D** moves laterally in a required direction of motion to a new position and lowers so that second cluster **153A, C** now supports movable element **152**. First cluster **153B, D** then moves laterally in an opposite direction from the first motion thereof and returns, without touching movable element **152**, to a starting position thereof while second cluster **153A, C** begins a similar cycle. The displacement in each step depends on the lateral amplitude of the motion of supporting fingers **153**, which is normally very small and many cycles may be required to achieve a required translation. Clearly, the lateral displacement may be reversed by reversing the cycles. By using two movable clusters of supporting fingers in succession, the displacement may be doubled from that of a single-cluster cycle, and so on. It is seen that the resultant effect is similar to that of the travelling wave actuator.

Actuation of the supporting elements can be by various methods, such as electrostatic actuation, whereby electrodes are placed around the supporting elements in the horizontal and vertical directions and voltages applied to bend or deflect the supporting elements, as required. Alternatively, the supporting elements can be made of piezoelectric material and, by applying suitable voltages, these piezoelectric beams may be bent in the horizontal and vertical directions. By controlling the timing and duration of these voltages it is possible to produce the required motion of the supporting element and rotate its extremity in clockwise or anticlockwise motions to advance or regress the movable part. Since static friction is necessary for the functioning of the device, as in the travelling wave option, the same method of holding and application of the normal force by using electrostatic or magnetic forces is used here.

This approach is particularly suitable in the micro-environment. Use of cumulative small displacements reduces stress on the elements. Moreover, at this scale, rotary motors would suffer dynamic friction sufficient to render them unusable.

A simpler variation of this actuator uses only one set of supporting fingers at each step, as shown in Figure 16. A movable element **162** is supported by actuated fingers **163A,B,C** while being moved, as previously explained, and, while actuated fingers **163A,B,C** return to an original position thereof, element **162** rests on stationary posts **164A,B**. Again, many cycles are needed to achieve a required lateral displacement.

Other variations and combinations of this device are possible. In another preferred embodiment, while the actuated elements retreat, the movable part is held by side handles instead of resting on top of aforementioned posts **164A,B**.

Emergency holding

In the event that the electrical supply fails, any electrostatic holding force stops and the movable element may fall. Of the various possible mechanisms, a preferred embodiment is presented that is designed having in mind the fabrication methods used in the micro-environment in which the device is used, but can also be applied in other fields. As shown in Figure 17a,b, an element **171** that needs holding in case of power failure is fabricated on a substrate **170**. A flexible element **172** is fabricated separated from element **171** by a sacrificial layer **174** that is later removed. Flexible element **172** is anchored at an end A and another end is held by a bistable buckling element **173** that is anchored at points B and C. In position 173A buckling element 173 is triggered by applying a suitable force in

order to make element **173** snap to another stable point **173B**, as shown in Figure **17c,d**. As a consequence, flexible element **172** is tensed, as shown in Figure **17c,d**, and thus holds free element **171** in position. In order to allow element **171** to move, element **172** is disengaged by an electrode **175**, isolated by insulation **176**, placed opposite element **172**. An applied voltage difference between element **172** and electrode **175**, attracts the former to the latter against the tension from buckling element **173** in position **173C**, which is displaced slightly from a stable position **173B** but insufficiently to cause it to snap to other stable position **173A**. In case of power failure, the attraction of electrode **175** ceases and the tension exerted by **173C** acts to return **172** to a position in which it holds movable element **171**.

Electro-mechanical aligning mechanism

With practically free movable elements, especially when a stepping motion is involved, there is a possibility of disalignment of the movable element in a direction perpendicular to the element's direction of motion. A mechanism for lateral realignment is necessary. A basic arrangement is shown in Figure 18. An element **184** to be kept aligned in a lateral direction **188** so that it remains in a rectilinear motion path **187** is situated between two aligning pads **183a** and **183b**, which are situated between walls **181a** and **181b** and attached respectively thereto by matched springs or other elastic elements **182**. Element **184** is movable in the plane of the drawing, which is perpendicular to the walls. Since the force of a spring is greater when displacement from equilibrium is greater, deviation of element **184** from center is corrected by spring action on both sides (Figure 18b). Springs **182** are retracted by electrostatic force between electrodes **185b** and **185c** in aligning pads **183a** and **183b** respectively and corresponding electrodes **185a** and **185d** at walls **181a** and **181b** respectively. When aligning elements **183a** and **183b** are retracted, free movement of movable element **184** is possible. Such aligning elements may also serve as the part of an actuating system that holds a movable element while the movable supporting elements of the finger actuation mechanism described earlier are retracted.

Another aligning option has the same layout as in Figure 18 but acts through electrostatic attraction between element **184** and elements **183a** and **183b**. One possibility is to connect element **184** to one polarity and elements **183a** and **183b** to an opposite polarity of a power supply. Another, preferred embodiment is to apply opposite polarity charges to elements **183a** and **183b**, represented generically as V_b and V_d in the figure. Opposite charges are induced in the respective adjacent surfaces of neutral element **184**. In either case the result is attraction between elements **183a** and **183b** and element **184**. When elements **183a** and **183b**

are in contact with 184. springs 182 will act to balance each other, thereby producing a net force that aligns movable element 184.

A variation of this principle is shown in Figure 19, wherein movable element 184 contains spring parts 182 that support aligning elements 183a and 183b. In one preferred embodiment, opposite electrostatic charges are applied to electrodes 185a and 185d, which are located at surrounding walls 181a and 181b. As before, these charges induce opposite charges in respective elements 183a and 183b which are attracted to respective walls 181a and 181b. Balanced springs 182 act to align element 184, as before.

These methods are applicable with magnetic or electromagnetic forces employed in place of electrostatic forces, with suitable variations that will be obvious to those experienced in the art. Other actuation methods, such as combined thermal or other action, can be applied.

Electrostatic aligning mechanism

Another electrostatic alignment mechanism follows directly from the envelope-like actuation principle discussed earlier. Aligning a movable element with electrostatic force alone will not work since electrostatic force depends inversely on distance. Thus any misalignment would be increasingly exacerbated. Using repulsive electrostatic forces would mitigate this problem although this is hard to implement in practice.

In the above discussion, however, it was shown that, in an envelope-like actuator with one or two external static electrodes, the force in the direction of surface motion depends on the derivative of the area with respect to distance in the direction of motion. It was also shown that, this being the case, if the profile of the electrode with the actuated element is such as to produce a large area variation, such as in the case of a suitable complex shape or fractal form, an increased force results. Based on this, shapes of the movable or static electrode can be tailored to produce a force depending differently on the distance from a rest position.

Using the same calculation as for envelope-like actuation, the electrostatic energy stored in a capacitor formed from two overlapping plates 201 and 202 is (Figure 20):

$$U = \frac{1}{2}\frac{\varepsilon_0 A}{g_0}V^2$$

the force is then:

$$F = -\frac{\varepsilon_0 V^2}{2g_0}\frac{\partial A}{\partial x}.$$

If two plates as shown in Figure 20b are used, the force is simply proportional to w_0, which is constant as the plate overlap changes. If, however, the profile of one plate be changed, for example to a triangle **203** as shown in Figure 20c, the force varies linearly with distance x and increases like $-2x.\tan\alpha$ as the overlap increases. However, in the configuration shown in Figure 20d, a reversed triangle 204 the force depends on $(x_0 - x)\tan\alpha$. It may be seen that when the distance of overlap is x_0 the force is zero, as would be expected. When there is no overlap the force is zero. If the overlap increases towards x_0 the force decreases, and *vice versa*. Application of this permits continuous alignment of an object that is movable in a plane parallel to the plane of the diagram, as shown in Figure 21, since displacement from alignment will result in a net attractive force to the central neutral point of the system. Two configurations are discussed, as shown in Figure 21a and b. In Figure 21a, triangular electrodes **210** are respectively fixed relative to walls **181** and central element **184** is movable; in Figure **21b** triangular electrodes **211** are fixed to movable element **184** and fixed electrodes **212** mounted on walls **181** have straight leading edges. Charges may be applied to the electrodes and to the movable plate by some means, shown generically by voltages V_a, V_b, V_c, and V_d in the figure. By this arrangement, central element **184**, which is intended to move along motion path **187**, may be constrained from lateral deviation in direction **188**.

Other electrode shapes may be tailored to produce different dependencies of the electrostatic force on the overlap distance. By combining these forms, complicated actuation effects, even including accelerations and decelerations, can be achieved. Another use of this concept is in the stabilization of electrostatic actuators such as in the envelope-type actuator. By placing shaped electrodes in opposition it is possible to stabilize the movable central electrode and prevent it from sticking to a side electrode as a result of the inherent instability of this actuator.

Valve Array

The single valve disclosed above is capable of switching light rays. Switching is possible between a single input and two outputs or two inputs into one output. The disclosed switch (Figure 22) can incorporate prior art optical devices, such as MEMS (Micro-Electro-Mechanical Systems) switches (*e.g.* mirrors), liquid crystals, and electro-optics.

In order to switch one input to two outputs, one mirror, **222**, parallel to a substrate, **223**, as disclosed before, moves in a direction parallel to substrate **223**, as illustrated by double-headed arrow **224** (Figure 22a, b). If the switch is in an OFF state, an input ray, **221A**,

emerges at output **221B**. If the switch is actuated to an ON state, ray **221A** reflects from mirror **222** and exits from output **221C**. Another embodiment can be designed (Figure 22c, d) wherein two inputs, **221A** and **221D**, are normal to each other and, in an OFF state, continue to respective outputs **221B** and **221C**. Actuating mirror 222 flips the output rays to emerge at interchanged outputs **221C** and **221B** respectively. In this latter embodiment, mirror **222** is reflective on both sides.

These are simple schemes, in which a single switching element is utilized, but the strength of this device – deriving from the compactness thereof – is in switching many inputs among many outputs, within a compact space. Elaborate examples can be produced by employing an array of switches (Figure 23a). (It should be noted that the terms "array" and "matrix" are used interchangeably herein.) A column of inputs, **231A ... 231D**, is situated normal to a coplanar row of outputs, **232A ... 232D**. At an intersection of each input line with each output line, a switching mirror, **233** for example, is placed, at an angle to an intersecting input line **231** and output line **232**; depending upon the switching technology being used, the angle may have any value up to 180°. It is emphasized that each input can act as an output, and *vice versa*, by reversing the respective ray propagation direction. In order to switch any particular input to any desired output, an appropriate switching mirror 233, at an intersection of corresponding input and output axes, is actuated to an ON state. For example, input **231B** may be directed to output **232D** by actuating switch **233A**. In the simplest case, only a single switch is actuated at any time in each row and in each column, resulting in a one-to-one correspondence between input and output rays: a "non-blocking" condition is said to exist. This is a non-broadcasting situation. When partly transmissive mirrors are used to allow broadcasting, "blocking" is allowed, in the sense that a light ray that enters the array along a row of switches may traverse, albeit diminished, two or more actuated switches, with a reflected ray being directed along each column wherein an actuated switch is situated.

Moreover, although inputs and outputs are generally normal to each other, more complicated switching operations, as basically described in Figs **22c** and **22d**, can be achieved by placing additional inputs **234** or outputs **235**, collinear with the original outputs and inputs respectively. In order to use these additional outputs or inputs, switches such as are illustrated in Figures **22c** and **22d** are used but none of the switches along the path of a respective ray is actuated, thus allowing unimpeded passage of the ray concerned. Such an array can be used for more complicated switching operations, as well as for controlling the beams.

In Figure 23b, another embodiment is presented in which only half of an array is needed. In this case, a static reflecting element, such as a mirror **239**, as shown, or a wave-guide termination, is placed at a diagonal of the array and that part of the array behind mirror **239** is discarded. All actuatable mirrors are double sided. In this configuration, fewer actuatable elements are required to achieve desired output configurations, with the same ray path-length as in the complete array of Figure 23a, although a ray may encounter more reflecting surfaces, leading to greater light loss. The overall switch is smaller, which is an advantage in some fabrication schemes, as will be shown below. In the example of Figure 23b, inputs **236A, B, C,** and **D,** are switched to outputs **237A, C, B,** and **D** respectively. Input **236A** is reflected to output **237A** *via* path α and input **236D** is reflected to output **237D** *via* path δ: it is seen that these require no switching. Input **236B** is, however, switched to output **237C** *via* path β by reflecting at the back of actuated mirror **238**. At the same time, input **236C** is switched to output **237B** *via* path γ by reflecting at mirror **238**. This description refers to mirrors as the actuatable elements but, as already mentioned, other switching elements having similar capabilities may be utilized.

More elaborate effects may be obtained by placing actuatable mirrors at the array diagonal, instead of a fixed mirror. As an example, placing two half-arrays, as previously described, back to back with the previously defined reflecting diagonal common to both. The two half-arrays may work independently but, if part of the reflecting bisecting element is switchable, it is possible for part of the rays to transit from one array to another.

Although the preceding preferred embodiments of valve arrays have no broadcast capability, these are not restrictive examples. Other embodiments can be devised wherein broadcasting is available by including mirrors that are partially reflective and partially transmissive, as mentioned above. In such cases, more than one switch is actuated, to produce broadcasting. Other schemes for broadcasting and multicasting can be designed by those skilled in the art, using the presented building blocks.

Most of the previous features of the array of switches are known from prior art and are applied to the specific embodiments disclosed here. In the case of small arrays, the number of switches is small and the short optical paths cause only small signal losses. Some applications, however, require large numbers of inputs and outputs. For a 10×10 array, 100 switches are required. A 50 μm separation between switches will result in a longest path length of ~1 mm. In a 100×100 array, however, there are 10,000 switches and the longest path length is 1 cm. The large increase in dimensions and number of switches results in increased losses.

A more elaborate switching device is now disclosed in which shorter paths and fewer switches are feasible. Other types of switches, both of the MEMS (microelectromechanical system) type, like the switch of the present invention, and of other types (lithium niobate, liquid crystal, *etc*), are also configurable in the arrays of the present invention, with MEMS switches being preferred.

An embodiment of this more elaborate device is presented schematically in Figure 24a. In an example of this embodiment, three virtual switching planes, **a, b,** and **c**, each having the capability of the arrays described in Figure 23a or 23b, are utilized. These virtual switching planes are, in effect, stacked, with corresponding elements vertically above one another. Each virtual switching plane operates either independently of the other virtual planes or in conjunction therewith. As will be seen below, these planes are not merely stacked, but may be mutually coupled, to achieve more efficient switching, in a smaller volume than is possible using prior art switch arrays.

It is important to note that the terminology "virtual plane", "virtual array", "virtual switching plane", "virtual switching array", and "logical switching array" has been adopted to stress that, the switching of the present invention is, in reality, done within the physical layers; i.e. the switches move parallel to the physical layers formed by the substrates whereon they are constructed. The virtual planes are only a descriptive artifice for comparison with previous art and better visualization of the overall switching effect. For this purpose, the switches are conceptually grouped in virtual planes independent of the physical layers. Each virtual switching plane, wherewithin any particular light path advances intersects the physical layers. The relationship between these two types of layers is shown in Figure 24a, where physical layers are drawn as vertical planes and labeled **α**, **β**, **γ**, **δ**, and **ε**, and virtual layers as horizontal planes labeled ***a***, ***b***, and ***c***. Further details are given below, in the section "Fabrication".

Inputs **241** consist of stacked rows, denoted by **a, b, c**, and vertical columns denoted by **I, II, III**. Outputs, **242**, are similarly denoted. The switch may be regarded as comprising a two-dimensional input array to a three-dimensional switch, leading to a two-dimensional output array. (The previously described device had a one-dimensional input array to a two-dimensional switch, leading to a one-dimensional output array.) With standard fabrication methods, it is difficult to realize the presented configuration; an easy fabrication method is described below. Those skilled in the art may find other fabrication possibilities. Other types of switches, beyond the preferred embodiments presented here, may be fabricated by the method presented in the following.

A realization of this arrangement is shown in Figure 24b, where a cut-away view of a two-layer array having four switches in each layer is shown, oriented similarly to the schematic view in Figure 24a. Inputs **243** may lead to outputs **244**. The upper layer has inputs **243** ***Ia*** and **243** ***IIa*** and outputs **244** ***Ia*** and **244** ***IIa***, and switches **A1**, **A2**, **A3**, and **A4**; possible light paths are illustrated by dotted lines. The lower layer has inputs **243** ***Ib*** and **243** ***IIb*** and outputs **244** ***Ib*** and **244** ***IIb***, and switches **B1**, **B2**, **B3**, and **B4**; possible light paths are illustrated by dashed lines. There is no interaction or correlation between the two layers. The switches may be of any suitable type.

The same Figure 24b can also illustrate the smallest realization of the half-array switch illustrated schematically in Figure 23b. In this case, mirrors **A1**, **A4**, **B1** and **B4** are fixed, mirrors **A3** and **B3** are absent, and mirrors **A2** and **B2** are actuatable, as before, and also reflective on both sides. Light paths beyond mirrors **A1**, **A4**, **B1** and **B4** are no longer possible. As in the previous paragraph, there is no interaction between the two layers.

In a first 3D embodiment presented, there is no correlation between input rows. A basic use of this stack is in connecting a number of inputs to outputs within a small space, the only advantage being a saving of space.

A more important use can, however, be envisioned in WDM (wavelength division multiplexing) networking wherein each plane is assigned to a different wavelength, there being a sufficient number of planes for the number of wavelengths in a multiplexed beam. Previously separated wavelengths are conducted to the respective planes wherein, for each wavelength, a 2D switching matrix routes inputs to desired outputs. These outputs may be subsequently recombined for further transmission or other use.

Although inputs **241** and **243** and outputs **242** and **244** are illustrated in Figure 24 as being respectively at right angles to each other, the switch array of the present invention may be configured with inputs and outputs at any convenient non-zero angle to each other.

Multi-layer switching

Another use of the 3D switching matrix shown in Figure 24 is in compact switching of a large number of inputs. The main purpose of this use is the reduction both of a ray path-length and the number of switches necessary compared with a square switching array. Instead of using a 2D array with a 1D column of inputs and of outputs, a 2D input matrix is utilized. Each plane, **a**, **b**, and **c**, consists of a non-blocking array. Such an array can be regarded as an operator that transforms the input row, **241** ***Ia***, **241** ***IIa***, **241** ***IIIa***, at plane **a**, to

output row, 242 *Ia*, 242 *IIa*, 242 *IIIa*, at plane a, and so on for the other planes. Since each plane is isolated from neighboring planes, the only possible operator action is to change a column index, *I*, *II*, *III*, ..., between input and output.

This is not enough: what is required is the ability to switch any input array element to any output array element. The 3D operator of the preceding paragraph is able to change only a column index of each element in the input matrix. This limitation can be overcome by a double application of the 3D operator wherein rows and columns at the output of a first stage are transposed into columns and rows at the input of a second stage. This second application of the operator will again change only the column index within each row of the second matrix, but this time the column indices are the former row indices. Thus, by applying the 3D operator represented by the 3D switching matrix twice in succession, with intermediate transposition, the necessary switching can be accomplished. Figure 25a illustrates the disposition of switching elements wherein, for convenience, mirrors are used as switching elements.

Practically, after rays transit a first switching matrix (**251**) emerging rays are introduced into a second similar switching matrix (**252**), rotated 90° with respect to matrix **251**. Matrix **252** may be switched differently from matrix **251**. Non-blocking switching can be achieved. It can, however, be shown that some switching configurations cannot be achieved, owing to the non-blocking property of the 2D arrays. A third switching matrix, rotated 90° with respect to matrix **252**, is added if the resulting overall switching is inadequate. This switch is actually a realization of the well known Clos architecture. With such a configuration, it can be proved that all switching permutations are obtainable. In this case, non-blocking states are again obtained although a non-blocking path that connects any given input to any given output may not be unique so this switch has inherent redundancy. This may be seen from Figure 25c which depicts a tri-cube complex switching array: a matrix of input beams **255** enters cube **256A**, wherein switching occurs, and the rays emerge as an output matrix **255'**. Matrix **255'** enters cube **256B**, which is a cube similar to, but with the switching planes thereof rotated with respect to cube **256A**, and emerges as transformed matrix **255''**. A third cube **256C** is used to make a final transformation of ray matrix **255''** into output matrix **255'''**. Cube **256C** is, again, rotated with respect to previous cube **256B**.

As an example of the advantage of this design, consider the task of switching any or several of 100 inputs to any or several of 100 outputs (a 100×100 switch). To perform the task, three switching matrices are needed in sequence, each matrix being rotated 90° with respect to a preceding matrix. Each switching matrix consists of a 10×10×10 cube, with 1000 switches --

a total of 3000 switches. The longest optical path, for a switch separation of 50 μm, is $(10+10+10+10+10)\times 50\ \mu m = 2500\ \mu m = 2.5$ mm. This compares with 10,000 switches and a 1 cm optical path needed to perform the same task with a conventional 2D array.

In Figure 25b is illustrated an equivalent switch array complex to that of Figure 25a, this time using the half-array 3D switching matrix of Figure 24b, wherein there are fixed mirrors along a diagonal of each matrix, instead of that of Figure 24a. In this case, a 100×100 switch requires only 1350 switches, not including the 100 fixed switches, along the diagonal.

As in the case of the two-dimensional matrix of Figure 23a, the three-dimensional arrays of Figures 24b and 25a can be configured with switches such as the switch illustrated in Figures 22c and 22d; providing the option of placing the arrays in switching states in which some or all input rays traverse the array without being reflected. In this case, too, special options, such as control elements along the transit paths, can be implemented. A 3D matrix need not be cubic and an input array may be, for example 10×10, 10×3, *etc*, provided that a following, rotated 3D matrix has a matching number of rows and columns. For example, for a six-input matrix, arranged as a 3×2 array, two planes of 3×3 arrays are needed. The second cube then needs three planes of 2×2 arrays.

In some cases it is necessary to ensure, while switching some inputs to other outputs, that some or all of the paths connecting the rest of the inputs to outputs are not disturbed. This concern is known as the rearrangement problem. With some configurations, a desired path change for some rays may require, at least momentarily, a switching off of other paths not related to the paths in question, and data intended to transit unaffected may be momentarily affected. This can be overcome with the 3D-block concept using additional cubes or blocks, together with the bypass capabilities of the switch (as explained before for the basic 2D arrays). To understand this concept we refer to Figure 25d, wherein, two identical tri-cube complex switching array sets, of the type shown in Figure 25c, are aligned each beside the other. Both sets **258A,B,C** and **259A,B,C** have identical switching capability. If only the first set be activated, switching occurs during the passage of input ray matrix **257** through **258A,B,C** exiting as matrix **257'''**. The rays then traverse cube **259C**, undisturbed, exiting as matrix **257***, which matrix is identical to **257'''**. Cube **259C** is in a bypass (or transparent) configuration, as explained earlier. At this stage, no ray enters cubes **259A** and **259B**.

If some change of switching configuration is needed, it can first be set up in cubes **259A** and **259B**. Then, cube **258A** is changed to transparent, bypass mode, simultaneously with a change of cube 259C into a desired switching configuration. In this case input ray matrix

257 traverses cube 258A unchanged, exiting as identical matrix 257a'. Matrix 257a' next enters block 259A, is switched therein into matrix 257a'' and thence by block 259B into matrix 257a''', finally emerging, after being switched by block 259C, as output matrix 257*. It may be seen that some of the paths linking input to output may pass through one set of cubes while other paths may pass at the same time through a second set of cubes: not all paths need go through the same set of cubes at the same time. The advantage of this design is that it does more than provide a solution to the rearrangement problem: the path redundancy that exists with only three cubes increases dramatically through the use of a second set of three cubes that doubles the system not only for rearrangement purposes but also provides the possibility of backup. Moreover, it can be seen that, even though the number of cubes has doubled, the path-length increases by only one block traverse thus almost not affecting properties depending on path length, such as loss. This set-up, featuring non-blocking and solving the rearrangement problem is known as a "strictly-non-blocking configuration".

As already mentioned, any kind of switch may be incorporated into the design, but switches including mirrors have many advantages and are a preferred embodiment. It is also emphasized that, although rays are shown as entering and exiting normal to a block, other angles of incidence and output can be designed for, depending on various considerations pertaining to the required final switching arrangements.

In addition to the coupling of two sets of blocks, the same additional states in which the input ray is not reconfigured by any switch (*i.e.* by-pass or transparent mode) can be utilized in other applications. Such a case or special option could be for implementation of control devices at the output of the by-pass path.

Again, the 3D matrix need not be cubic and the input array may be for example 10×4, 10×3, *etc*, provided that the rotated 3D matrix has a corresponding number of rows and columns. For a six-input matrix arranged as a 3×2 array, two planes of 3×3 arrays are needed. The following cube will need three planes of 2×2 arrays.

Based on the elements presented, those skilled in the art may find other variations covered by this invention. One possible variation is to alter the number of cubes used, applying one, two, three, four, *etc*, cubes as required. Not only may the number of cubes change but also their mutual disposition, as required by the specific application. Other wave-shaping or controlling elements can obviously be inserted before, between, or after the switching cubes. Such variations include the use of lenses, wave regenerators, prisms, magnets, *etc*. or addition of a color de-multiplexing system to the above methods.

The 3D blocks explained above have multiple switching capabilities. Although described basically as a cross-connect for optical communications, a device having such switching capabilities can serve as a logical component and thus be utilized as part of an optical memory or as part of an optical computing device.

Wavelength de-multiplexing

Another embodiment includes the addition of a wavelength demultiplexing/multiplexing system to the above methods for use of the disclosed switch in WDM (wavelength division multiplexing). In this embodiment, information is transmitted through optical fiber, encoded within a group of different wavelengths. A wavelength de-multiplexing and multiplexing device is necessary to separate the different wavelengths at the entrance to a switch array and, after processing or use, to recombine these wavelengths. Rays introduced into the described switch are preferably parallel to one another. A device that can accomplish this is presented.

Several technologies for wavelength separation exist, among them, the use of diffraction gratings. The embodiment introduced below uses reflection gratings to separate the wavelengths into parallel rays that can be introduced into a 3D switch. A similar device collects and recombines the output bundle of parallel rays for insertion into a fiber.

The device used (Figure 26) includes two parallel reflection gratings, **261** and **262**, with respective diffracting surfaces that face each other and with rulings also parallel. The distance between the separated wavelength rays is determined by parameters including the distance *d* between parallel gratings **261** and **262** and the pitch of the grating rulings.

A collimated input beam, **263**, emerging from a fiber, is incident on a surface of first reflection grating **261** at a predetermined angle α. A simple mirror would reflect this beam at the same angle with respect to a normal to the surface of the mirror. A grating, however, reflects different wavelengths (λ_1, λ_2, λ_3, ...) at different angles (β_1, β_2, β_3, ...): the sum of angle of incidence plus angle of diffraction is a function of wavelength. From this, it is clear that different wavelengths will be separated into different angles at reflection grating **261**.

Since the relation between the incidence and reflection angles is the same for second reflection grating **262** as for first reflection grating **261**, and since the gratings are parallel, the reflected angle from second grating **262** is equal to the angle of incidence α at first grating **261**. Since this angle α is equal for all wavelengths, rays of all wavelengths emerge

parallel, at angle α, but displaced from one another after reflecting from second grating 262. Thus, wavelengths are separated into parallel rays, with displacement depending upon inter-grating distance *d*, incident angle α, and the pitch of grating rulings.

Since the ray paths are reversible, reversing direction provides a device capable of recombining wavelengths before insertion into a fiber on output. The use of one device at an input to the matrix and a reversed one at an output allows de-multiplexing, switching, and multiplexing signals in a WDM network.

The switch presented can thus be used for diverting input rays of different wavelengths from a plurality of inputs to a plurality of outputs. The primary use is in communications. Together with the wavelength separation and combination device presented, the switch is applicable to WDM. Other applications, such as optical computation, *etc.* are also possible.

Fabrication

Since the real strength of this device – residing in its compactness – is in switching among many inputs and many outputs, these switches are envisioned to be incorporated in multi-switch devices.

The three-dimensional arrays described in the present invention may be fabricated using prior art technologies, such as conventional macro-, meso- and micro-machining techniques. In one envisioned application, the switching of optical paths, the fabrication methods include photo-lithography, deposition, and etching, all methods commonly used in microelectronics and micro-machining. These methods may, however, be uneconomical or impractical. Therefore, the scope of the present invention includes an innovative method of fabricating these arrays, which enhances the advantages thereof.

In this process, 3D arrays are produced using 2D fabrication methods and stacking to obtain the desired 3D switching array, such as an optical cross-connect (OXC). The fabrication technique transfers the critical steps into the macro-fabrication realm, where high quality can be achieved with already-existing mature techniques and much experience exists. The results are applied in the micro-realm.

The basic device is fabricated on top of a wafer surface, in contrast to previous art, where the mirrors are etched into or erected upon a substrate. The mirrors, which require substantially perfect surface quality, flatness, and parallelism, take advantage of high-quality substrates

prepared for the microelectronics industry. Substrates of various dimensions, thicknesses, materials, and surface preparations are available.

Generally, the device can be prepared on any kind of material and the fabrication procedure is independent of substrate material. While the substrate material has no effect on the switches, apart from surface preparation and physical dimensions, it is possible to take advantage of a substrate's properties. For example, electronic circuitry may be integrated into the substrate or optical fibers may be set therein, in which case advantage can be taken of features such as the crystallographic planes of the substrate material, as in silicon. Those skilled in the art may find different materials and techniques for the production of these switches. The fabrication techniques introduced here may be useful for other applications and not just for mirrors or switches as in the disclosed invention.

The fabrication methods disclosed, in many aspects, are enabling technologies. In other switch array configurations the MEMS methods impose restrictions that impede the functioning and the reliability of the device. The usual MEMS fabrication methods are inherently two-dimensional. That is to say, the device is like a silhouette. If a device should require any out-of-plane structure, the elements prepared at the surface have to be raised. In many cases this is not a problem but, when dealing with free-space arrays for optical switching, this introduces severe restrictions. The principal deficiency is the impossibility of truly positioning the mirrors (a variation of 0.1 degree is enough to spoil the usefulness of the device). Another aspect is mirror quality: mirror smoothness affects signal loss. When dealing with large arrays of mirrors, and especially in 3D configurations, this becomes a disqualifying factor.

Single-switch fabrication

Fabrication is explained with respect to an actuated mirror application. One starts with an optical quality polished substrate **272** (Figure 27). Mirror material **271**, generally a metal such as aluminum, is deposited on substrate **272** and patterned using standard methods such as lithography. Generally, mirror **271** is produced on top of substrate **272** at a zone **273** where substrate material eventually will be removed so that a ray may pass through (Figure 27b).

In a variant fabrication procedure (Figure 27c, d), a sacrificial layer **274** is deposited on top of substrate **272**; patterned, if necessary, to allow the deposition of subsequent layers that must penetrate sacrificial layer **274** to reach substrate **272**; and polished prior to deposition

and patterning of mirror 271. As well as mirror 271, supporting beams 275 are deposited and patterned above and through sacrificial layer 274. Supporting beams 275 can be made of any material: in many cases they are made of metal or otherwise include conductive material. Supporting beams 275 are fabricated attached to mirror 271 and substrate 272. The number and configuration of supporting beams 275 depend on the application.

After deposition and patterning of mirror 271 and supporting beams 275, these movable elements are released by dissolving sacrificial layer 274 (Figure 27d) or by etching away a non-required, and hence superfluous, part of substrate 272 under mirror 271 (Figure 27b), thus leaving mirror 271 suspended by beams 275. Further fabrication steps depend on the actuation mechanism. Since the surface on which mirror 271 is deposited was previously polished, the quality of mirror 271 resembles the high quality of the surface on which it was constructed. The use of a surface polished by conventional means to optical mirror grade and the use of this surface as the base for mirror preparation are key innovations of this method.

Fabrication of electrodes and conducting lines can be done together with, before, or after the above-mentioned steps. Electrodes, conducting lines and the like, as well as the above-mentioned supporting beams 275, are referred to collectively herein as "auxiliary elements".

In case of envelope actuation (Figure 27e, f), an electrode 276 is deposited on substrate 272 and covered by a sacrificial layer 274. The above-mentioned steps for fabrication of mirror 271 are carried out on top thereof. A second electrode of the envelope can be produced in one of several ways. In one way (Figure 27e, f) mirror 271 is covered by a second sacrificial layer 274A. Second layer 274A is patterned and covered by a second envelope electrode 277, which is also patterned. By removing sacrificial layers, the envelope is formed and mirror 271 is released.

Another possibility is depositing and patterning a second envelope electrode 277 on another side of substrate 272 or, as illustrated in Figure 27g, on another substrate 272A. By aligning and bringing together a mirror side of substrate 272 and a second-electrode side of substrate 272A, and bonding, an envelope is formed (Figure 27h). Bonding is done by one of the known wafer-bonding methods, such as fusion bonding, anodic bonding, or other bonding methods. Spacers and electrical connection paths are deposited and patterned as required prior to alignment and bonding.

In the case of curved electrode actuation, the mirror can be processed directly on a wafer surface at a ray traverse zone. Supporting beams are deposited and patterned on top of the mirror, as previously explained. It is possible to deposit material for the static curved electrode and to do the patterning simultaneously, followed by insulation deposition and patterning over the static electrode. Etching the sacrificial layer and corresponding substrate area releases the movable elements.

In the case of magnetic actuation, the supporting beams may act also as conducting lines, and there is no need for further fabrication steps. The mirror and beams are fabricated and released, as described above.

Other methods for single-switch fabrication can be devised by those skilled in the art. It is emphasized, however, that fabrication on the substrate surface is critical to obtaining good quality mirrors and acquiring better control over alignment of the mirrors.

Switch array fabrication

The construction of a switch array requires more elaborate methods than single-switch fabrication. The disclosed method is designed to facilitate accurate construction of a 3D cubic array. Switches are made on wafers in rows and a number of wafers are bonded each on top of another, but displaced laterally, to produce a 3D array. In the following the fabrication is exemplified by mirrors, although other switching elements can be used instead and formed into a 3D-matrix device. This fabrication method can be applied to other devices that can take advantage of the planarity of the wafers and the 3D configuration of the completed device.

In order to simplify understanding of the fabrication method, a 4×4×4 array is described (Figure 28). It is to be understood that the descriptions below are illustrative, and are not intended to restrict the present invention to the specific details set forth below

Single switches **281** are produced, as described previously, in rows **283**, on a surface **282** of a substrate. In our example, there are four rows. These switches are also arranged in groups **285** of regularly spaced columns **284**, each group being separated from a neighboring group by an empty column **286** at the same column spacing. The first group of our example consists of one column of four rows (1×4), separated by an empty column from a second group consisting of two columns of four rows (2×4) followed by another empty column. The

arrangement continues with successive groups of 3×4 and 4×4 to form a set. An entire wafer may be covered with such sets. For our example, at least seven such sets are required.

In order to fabricate a box array, these sets are carefully aligned, each on top of another, and bonded. A first set is placed at the bottom ready for an alignment (Figure 28b). A second wafer is aligned on top of and parallel to the first, with a second group of columns (2×4) centered above a single-column group (1×4) of the first wafer. This alignment is obtained by suitably displacing the second wafer with respect to the first, in a direction parallel to rows **283**. This procedure is continued with consecutive wafers, a 3×4 group of columns being centered above the 2×4 group, and a 4×4 group being centered above the 3×4. Stacking is then continued in a reverse order, a 3×4 group being centered above the 4×4 group, and so on, until a 1×4 group is placed on top of a second 2×4 group. The stack is then bonded. The wafer surfaces correspond to the physical layers defined earlier. Viewed from the side, however, the mirrors form a 2D matrix having column **287** and row **288** directions oriented at 45° to the surfaces of substrates **282**. The mirrors are oriented at 45° to these column and row directions. In this example, there are four virtual arrays, corresponding to the four rows of switches fabricated on the wafer surfaces.

If the configuration shown in Figure 23b is fabricated, only half of the above array is required. One set of switching mirrors, at a reflecting middle plain, **289**, is replaced by a plain static mirror substrate and the mirrors on the non-reflective side of plain **289** are not required.

After bonding is completed, the mass is accurately diced, preferably parallel to columns **287** and rows **288** of the mirror array, along dashed lines **280**. A cubic array of mirrors results. This array is further packaged by aligning with input and output fibers. It is possible to align two or more such cubes and to rotate one with respect to another so that a 3D-switching device, as explained before, is produced.

A finished device is represented in Figure 29. There, a finished cube can be seen with aligned substrates **291** bonded at interfaces **294**. The input and output ports for the rays, in the case of an optical switch, are represented interchangeably by **292** and **293**.

Similar steps are followed to produce arrays of other dimensions, including rectangular arrays other than square ones.

Operation

These switches are actuated by one of the previously specified methods through conducting lines which connect rows, columns, and planes, as appropriate. By applying an appropriate voltage or current to a particular mirror, that mirror may be set or reset into an ON or OFF state.

Applications

The switch presented can be used for switching input rays of different wavelengths from numerous input paths to numerous output paths. It is primarily intended for use in communications. Together with the wavelength separation and re-combination device disclosed above, it is applicable to WDM. Other applications, such as in optical computation, *etc.* will be evident.

While the invention has been described with respect to a limited number of embodiments, it will be appreciated that many variations, modifications and other applications of the invention may be made.

What is Claimed Is:

1. An optical switch for switching a light ray comprising:

   (a) a substantially planar substrate having a portion that is transparent to the light ray;

   (b) a switching element having at least one reflective surface substantially parallel to said substrate; and

   (c) a bistable mechanism for moving said switching element in a direction parallel to said substrate between:

      (i) a first position wherein the light ray traverses said transparent portion of said substrate and

      (ii) a second position wherein the light ray is blocked from traversing said transparent portion of said substrate and wherein the light ray is reflected by said reflective surface.

2. The optical switch of claim 1, wherein said mechanism includes:

      (i) a first rigid element having two ends, a first said end of said first rigid element being flexibly connected to a fixed point;

      (ii) a second rigid element having two ends, a second said end of said first rigid element being flexibly connected to a first said end of said second rigid element; and

      (iii) a tensile elastic element connecting said first end of said first rigid element to a second said end of said second rigid element so that a distance between said first end and said second end when said elastic element is in a relaxed state is less than a sum of a distance between said ends of said first rigid element and a distance between said ends of said second rigid element;

   both said rigid elements being constrained to be movable only in a plane parallel to said substrate.

3. The optical switch of claim 1, wherein said mechanism includes:

      (i) a first element having two ends;

(ii) a second element having two ends. a first said end of said first element being flexibly connected to a first said end of said second element;

(iii) a third element having two ends. a second said end of said second element being flexibly connected to a first said end of said third element;

(iv) a fourth element having two ends. a second said end of said third element being flexibly connected to a first said end of said fourth element;

(v) two fixed anchor points. a second said end of said first element being flexibly connected to a first said anchor point and a second said end of said fourth element being flexibly connected to a second said anchor point: and

(vi) a tensile elastic mechanism for maintaining said mechanism for moving said switching element in either of two stable states;

all said elements being constrained to be movable only in a plane parallel to said substrate.

4. The optical switch of claim 3 wherein all said elements are rigid.

5. The optical switch of claim 4 wherein said tensile elastic mechanism includes:

a) a tensile elastic element connecting said second end of said second element to said first anchor point so that a distance between said second end and said first anchor point when said elastic element is in a relaxed state is less than a sum of a distance between said ends of said first element and a distance between said ends of said second element: and

b) a tensile elastic element connecting said first end of said third element to said second anchor point so that a distance between said first end and said second anchor point when said elastic element is in a relaxed state is less than a sum of a distance between said ends of said third element and a distance between said ends of said fourth element.

6. The optical switch of claim 4 wherein said tensile elastic mechanism includes a tensile elastic element connecting said first end of said second element to said second end of said third element so that a distance between said first end and said

second end when said elastic element is in a relaxed state is less than a sum of a distance between said ends of said second element and a distance between said ends of said third element.

7. The optical switch of claim 4 wherein said tensile elastic mechanism includes a spiral spring at each said flexible connection.

8. The optical switch of claim 3 wherein:

   a) said first element and said fourth element are elastic beams,

   b) said second element and said third element are rigid,

   c) said first element is rigidly connected to said first anchor point, and

   d) said fourth element is rigidly connected to said second anchor point.

9. A hinge comprising:

   a) a housing having a flat wall,

   b) an element free to roll within said housing and having a connector that protrudes beyond said housing, and

   c) a mechanism for urging said rollable element against said wall as said element rolls within said housing so as to maintain rolling contact between said element and said wall.

10. The hinge of claim 9 wherein said connector is a rigid arm.

11. The hinge of claim 9 wherein said mechanism is electrostatic.

12. The hinge of claim 9 wherein said mechanism is magnetic.

13. The hinge of claim 9 further comprising:

   d) a restoring mechanism for returning said rollable element to contact with said wall in case of loss of said contact.

14. The hinge of claim 13 wherein said restoring mechanism includes:

   a) two flexible cables:

      (i) a first end of a first said cable being operationally connected to but electrically insulated from said housing,

(ii) a first end of a second said cable being operationally connected to but electrically insulated from said housing,

(iii) a second end of said first cable being operationally connected to but electrically insulated from said rollable element, and

(iv) a second end of said second cable being operationally connected to but electrically insulated from said rollable element;

b) two electrodes for resetting said rollable element in place:

(i) a first said electrode being situated opposite first said cable on a side away from said rollable element, and

(ii) a second said electrode being situated opposite second said cable on a side away from said rollable element;

c) a mechanism for charging said electrodes; and

d) a mechanism for charging said cables.

15. The restoring mechanism of claim 14 wherein:

a) said cables are slack while said rollable element is in contact with said wall, and

b) at least one said cable is taut when said rollable element loses contact with said wall.

16. A travelling wave actuator for moving an object comprising:

a) an elastic membrane,

b) a mechanism for maintaining contact between the object and said membrane, and

c) a mechanism for generating a travelling wave in said membrane.

17. The travelling wave actuator of claim 16 further comprising:

d) a substrate whereupon said elastic membrane is deposited.

18. The travelling wave actuator of claim 16 wherein said mechanism for maintaining contact is electrostatic.

19. The travelling wave actuator of claim 16 wherein said mechanism for maintaining contact is magnetic.

20. The travelling wave actuator of claim 16 wherein said mechanism for generating a travelling wave includes:

    (i) a plurality of electrode pairs, equally spaced along and straddling said membrane, and

    (ii) for each said pair, a respective alternating electrical power supply.

21. The travelling wave actuator of claim 16 wherein said means of generating a travelling wave is magnetic.

22. The travelling wave actuator of claim 16 wherein said means of generating a travelling wave is thermal.

23. The travelling wave actuator of claim 16 wherein said means of generating a travelling wave is piezoelectric.

24. An actuator for moving an element comprising:

    a) a stationary support for the element,

    b) a deflectable support for the element operative to:

        (i) raise the element from said stationary support,

        (ii) advance the element in a required direction of motion,

        (iii) deposit the element upon said stationary support, and

        (iv) return to a starting position thereof.

25. The actuator of claim 24 wherein:

    a) said stationary support includes a cluster of fingers, said cluster being sufficient to support the element, and

    b) said deflectable movable support includes at least one cluster of fingers, each said cluster being sufficient to support the element.

26. The actuator of claim 25 wherein each said finger includes a surface at a tip thereof, whereupon said element is supportable.

27. The actuator of claim 24 wherein the element is a planar switching element.

28. The actuator of claim 24 wherein said deflectable support is activated electrostatically.

29. The actuator of claim 24 wherein said deflectable support is activated piezo-electrically.

30. An emergency holding device for a movable switching element comprising:

a) a buckled beam having:

(i) a first stable configuration concave towards the switching element, and

(ii) a second, tense configuration, concave towards the switching element, wherefrom, if relieved, said beam relaxes to said first stable configuration; and

b) a flexible strap straddling the switching element, said strap being:

(i) attached at a first end thereof to a center of said beam and perpendicular thereto, and

(ii) anchored at a second end thereof at a fixed point,

so that, at said concave stable configuration, said strap constrains the switching element.

31. The emergency holding device of claim 30 wherein said strap is electrically conductive, the device further comprising:

c) an electrode placed opposite said strap.

32. A mechanism for lateral realignment of a free movable element with respect to a rectilinear motion path thereof comprising:

a) two alignment pads on opposite sides of the element,

b) a mechanism for bringing said pads into contact with the movable element, thereby nudging the element to said laterally aligned position, and

c) a mechanism for retracting said pads from said contact.

33. The realignment mechanism of claim 32 wherein each said alignment pad includes an electrode.

34. The realignment mechanism of claim 32 wherein said contact mechanism is elastic.

35. The realignment mechanism of claim 32 wherein said contact mechanism is electrostatic.

36. The realignment mechanism of claim 32 further comprising:

d) two walls situated on opposite sides of the movable element and outside said alignment pads, and

e) elastic elements attaching each said alignment pad to a nearer said wall.

37. The realignment mechanism of claim 32 further comprising:

d) two walls situated on opposite sides of the movable element and outside said alignment pads, each said wall including an electrode, and

e) elastic elements attaching each alignment pad to a nearer side of the movable element.

38. The realignment mechanism of claim 32 wherein said retracting mechanism is electrostatic.

39. The realignment mechanism of claim 32 wherein said retracting mechanism is magnetic.

40. A mechanism for continuous lateral realignment of a free movable element with respect to a motion path thereof comprising:

a) a stationary electrode adjacent to and clear of the path,

b) a second, movable electrode:

(i) attached to the element,

(ii) at least partially overlapping said stationary electrode, and

(iii) constrained to remain parallel to said stationary electrode so that a gap remains therebetween, and

c) a mechanism for electrostatically charging said electrodes, the resulting electrostatic force between said electrodes acting to maintain the element in the motion path.

41. The realignment mechanism of claim 40, wherein the motion path is confined to a plane.

42. The realignment mechanism of claim 41, wherein the motion path is rectilinear.

43. The realignment mechanism of claim 40, further comprising:

d) a second stationary electrode adjacent to and clear of the path,

(i) lying in a same plane as and clear of said first stationary electrode.

(ii) opposed to said first stationary electrode with respect to the motion path, and

(iii) at least partially overlapped by said movable electrode so that a gap remains therebetween, and

e) a mechanism for electrostatically charging said second stationary electrode, the resulting electrostatic force between said electrodes acting to maintain the element in the motion path.

44. The realignment mechanism of claim 43 wherein said stationary electrodes are shaped as mutual mirror images and are symmetrically disposed about the path.

45. The realignment mechanism of claim 43 wherein said charge on said second stationary electrode is of a same polarity as said charge on first said stationary electrode.

46. The realignment mechanism of claim 45 wherein said charge on said movable electrode is of a same polarity as said charge on said stationary electrodes.

47. The realignment mechanism of claim 45 wherein said charge on said movable electrode is of opposite polarity to said charge on said stationary electrodes.

48. The realignment mechanism of claim 44 wherein said shape of each said electrode is an isosceles triangle, an axis of symmetry whereof is oriented perpendicular to the motion path.

49. A method of moving an element comprising the steps of:

a) urging the element to be in contact with an elastic membrane while

b) generating a travelling wave in said membrane.

50. A method of moving an element comprising the steps of:

a) providing:

(i) a stationary support for the element. and

(ii) a deflectable support for the element. and

b) cyclically operating said deflectable support to:

(i) raise the element from said stationary support.

(ii) advance the element in a required direction of motion.

(iii) deposit the element upon said stationary support. and

(iv) return to a starting position thereof.

51. A method of holding an electrostatically supported switching element upon cessation of a supply of power to the switching element. comprising the steps of:

a) providing a flexible strap straddling the switching element. and having a first configuration wherein said strap constrains the switching element and a second configuration wherein the switching element is free from said constraint; and

b) maintaining said strap in said second configuration only while the power is supplied.

52. A method of laterally realigning a free movable element in a direction perpendicular to a rectilinear motion path thereof comprising the steps of:

a) providing a realignment mechanism including two movable alignment pads on opposite sides of the element.

b) bringing said pads into contact with the movable element. thereby nudging the element to the rectilinear motion path. and

c) retracting said pads.

53. A method of continuously laterally realigning a free movable element with respect to a motion path thereof comprising the steps of:

a) providing:

(i) a stationary electrode adjacent to and clear of the path.

(ii) a second. movable electrode attached to the element. at least partially overlapping said stationary electrode. and constrained to remain parallel to said stationary electrode so that a gap remains therebetween. and

(iii) a mechanism for electrostatically charging said electrodes; and

b) electrostatically charging said electrodes.

54. The method of claim 53 further comprising the step of:

c) providing:

(i) a second stationary electrode adjacent to and clear of the path, lying in a same plane as and clear of said first stationary electrode, opposed to said first stationary electrode with respect to the motion path, and at least partially overlapped by said movable electrode so that a gap remains therebetween, and

(ii) a mechanism for electrostatically charging said second stationary electrode.

55. The method of claim 54 wherein said stationary electrodes are shaped as mutual mirror images and are symmetrically disposed about the path.

56. The method of claim 54 further comprising the step of charging said second stationary electrode with a same polarity as said charge on said first stationary electrode.

57. The method of claim 56 further comprising the step of charging said movable electrode with a same polarity as said charge on said stationary electrodes.

58. The method of claim 56 further comprising the step of charging said movable electrode with a polarity opposite to said charge on said stationary electrodes.

59. The method of claim 55 wherein said stationary electrodes are shaped as isosceles triangles.

60. A method of fabricating a micro-device having a high-quality smooth mirror surface comprising the steps of:

a) polishing a substrate surface to a required smoothness,

b) depositing mirror material on said substrate, and

c) removing a superfluous part of said substrate adjacent to a surface of said mirror.

61. A method of fabricating a micro-device having a high-quality smooth mirror surface comprising the steps of:

a) depositing a sacrificial layer on said substrate.

b) polishing a surface of said sacrificial layer to a required smoothness.

c) patterning said sacrificial layer to provide for auxiliary elements.

d) depositing mirror material on said polished surface of said sacrificial layer.

e) depositing said auxiliary elements on said patterned portion of said sacrificial layer, and

f) removing said sacrificial layer.

62. The method of claim 61, comprising the further step of:

g) removing a superfluous part of said substrate.

63. A method of fabricating an envelope-actuated micro-device having a high-quality smooth mirror surface comprising the steps of:

a) providing a first substrate.

b) depositing an electrode on said first substrate.

c) depositing a first sacrificial layer on said electrode and said first substrate.

d) polishing a surface of said first sacrificial layer to a required smoothness.

e) patterning said first sacrificial layer to provide for a first set of auxiliary elements.

f) depositing mirror material on said polished surface of said first sacrificial layer, and

g) depositing said auxiliary elements on said patterned portion of said first sacrificial layer.

64. The method of claim 63, comprising the further step of:

h) providing a second electrode.

65. The method of claim 64 wherein said providing of said second electrode is effected by steps including:

(i) depositing a second sacrificial layer on said mirror material.

(ii) patterning said second sacrificial layer to provide for said second electrode and a second set of auxiliary elements. and

(iii) depositing said second electrode and said second set of auxiliary elements on said patterned portion of said second sacrificial layer.

66. The method of claim 64 wherein said providing of said second electrode is effected by steps including:

(i) providing a second substrate.

(ii) depositing said second electrode on said second substrate,

(iii) aligning said second electrode opposite the micro-device as fabricated on said first substrate. and

(iv) bonding said second substrate to said first substrate.

67. The method of claim 63. comprising the further step of:

h) removing said first sacrificial layer.

68. The method of claim 63, comprising the further step of:

h) removing a superfluous part of said substrate.

69. A mechanism for providing a strictly non-blocking switching configuration comprising two coupled substantially identical tri-cube complex switching arrays:

a) each said array being operative to switch any input element to any output element.

b) a first said array being operative to allow any input element to transit unswitched to a corresponding input of a second said array. and

c) said second array being operative to allow any output element from said first array to transit unswitched to a corresponding output of said second array.

70. A method of strictly non-blocking switching including the steps of:

a) providing two coupled substantially identical tri-cube complex switching arrays:

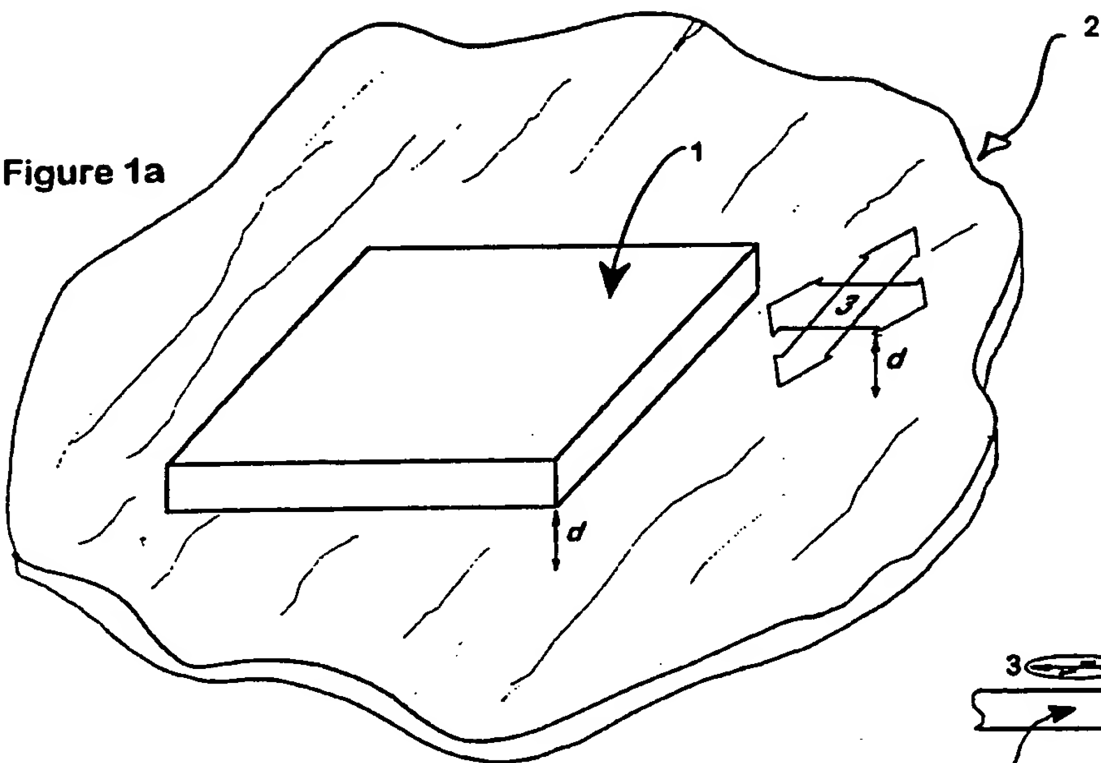
(i) each said array being operative to switch any input element to any output element.

(ii) a first said array being operative to allow any input element to transit unswitched to a corresponding input of a second said array, and

(iii) said second array being operative to allow any output element from said first array to transit unswitched to a corresponding output of said second array; and

b) operating said switching arrays coupled in parallel.

Figure 1a



Side Elevation

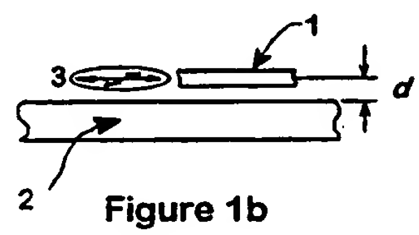
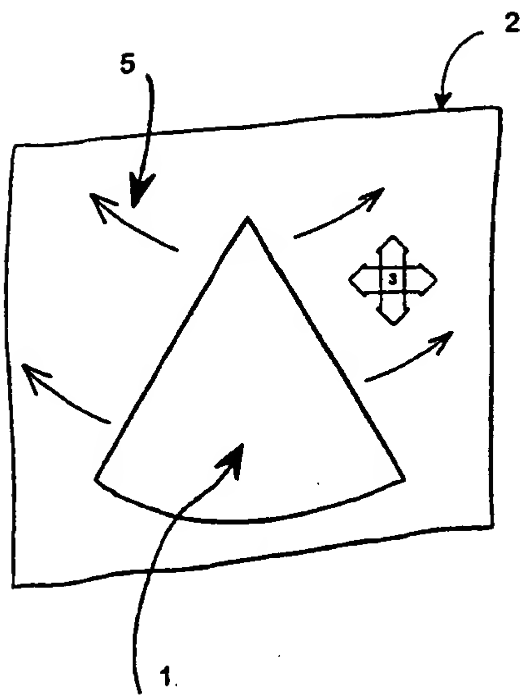


Figure 1b



Plan View

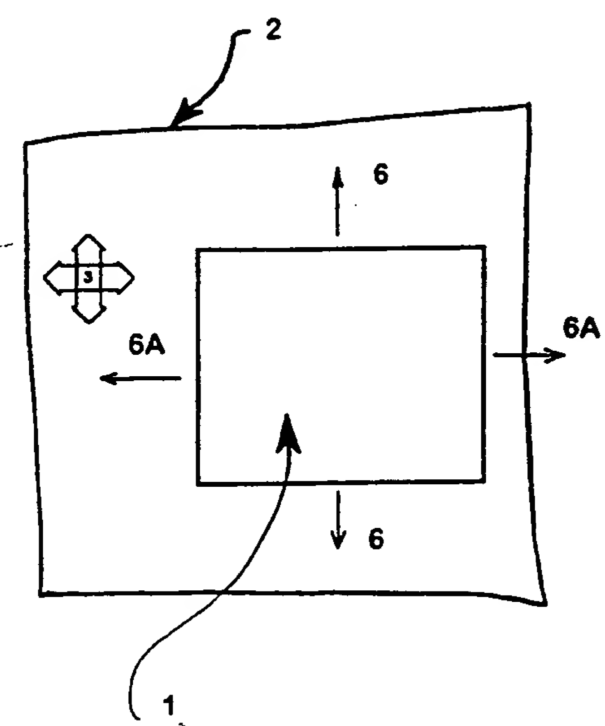


Figure 1c

Figure 1d

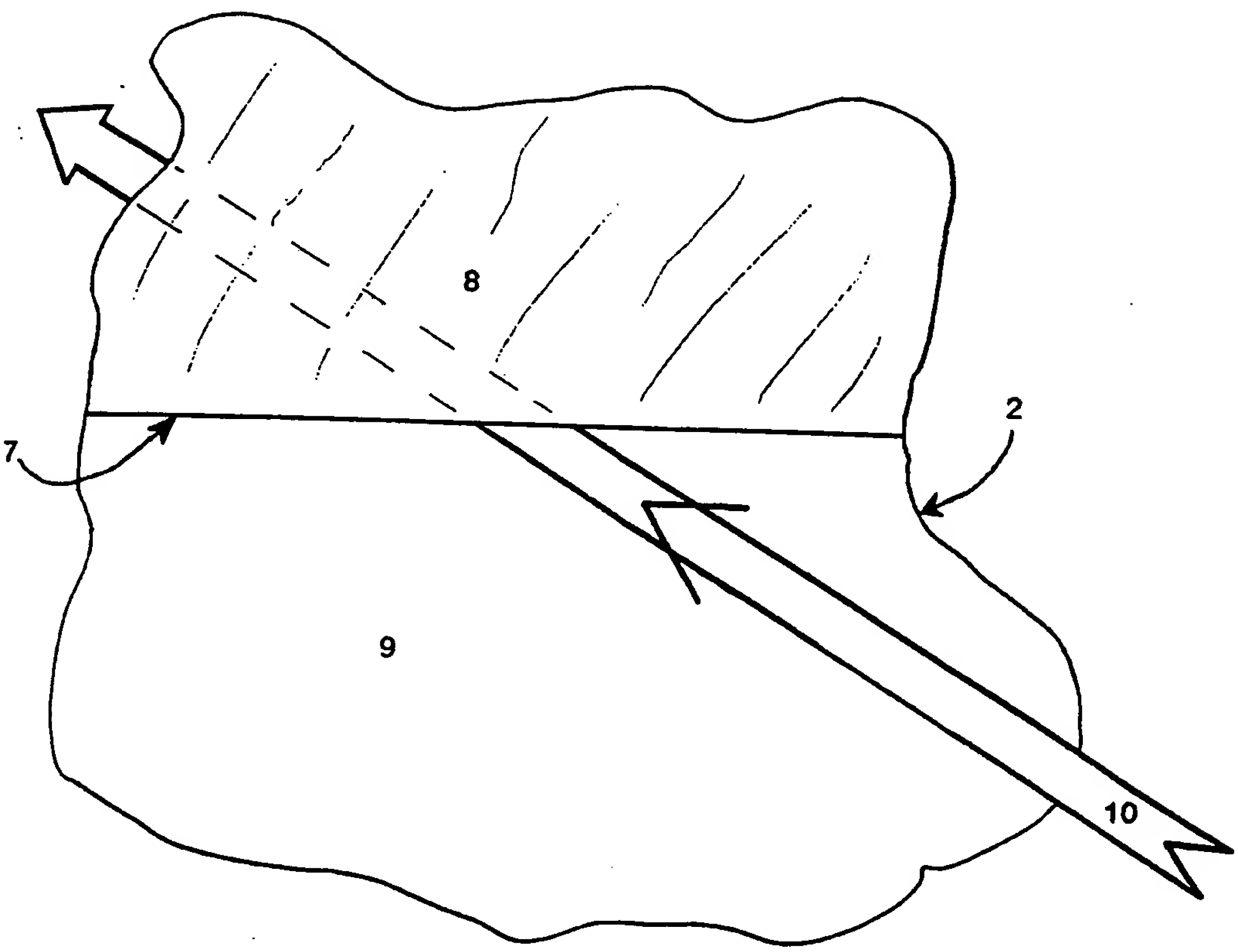


Figure 2

Side Elevation

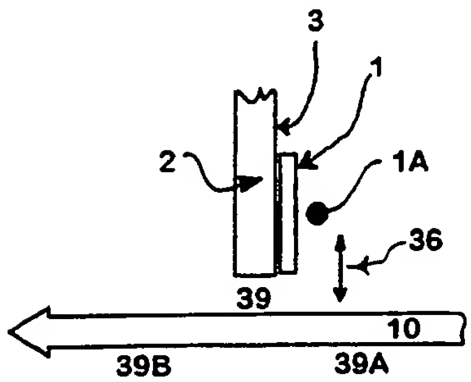


Figure 3a

OFF

Plan View

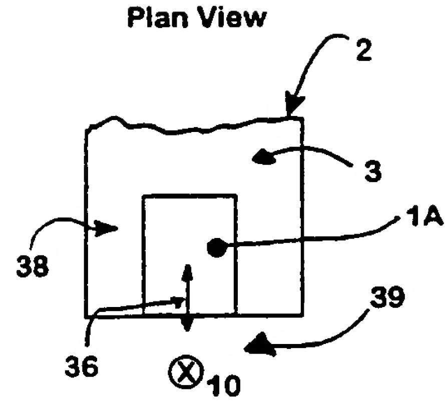


Figure 3b

Side Elevation

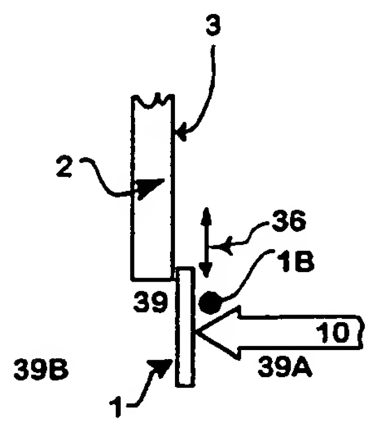


Figure 3c

ON

Plan View

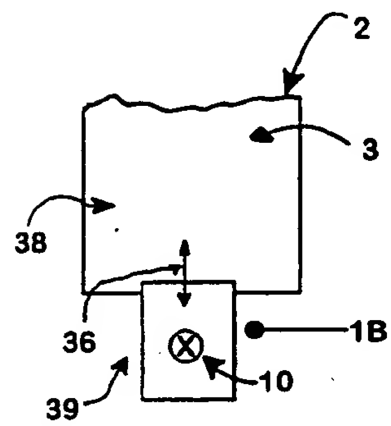


Figure 3d

Side Elevation

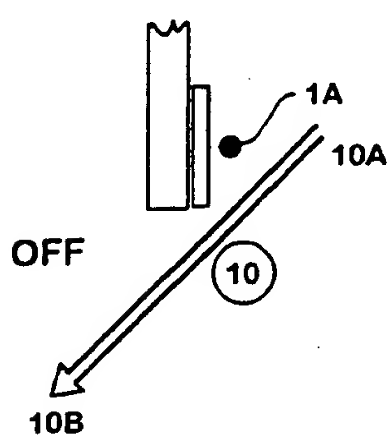


Figure 3e

Side Elevation

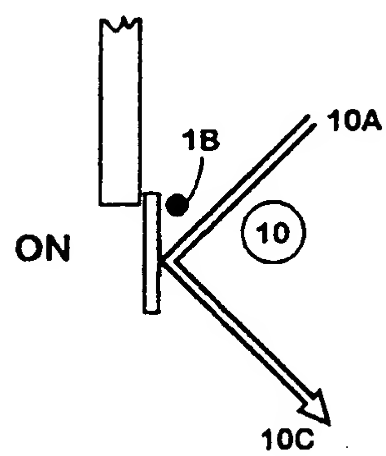


Figure 3f

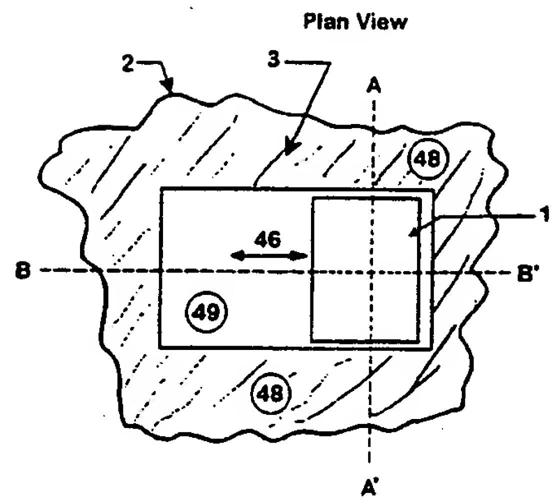


Figure 4a

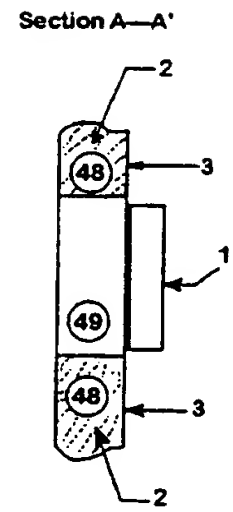


Figure 4b

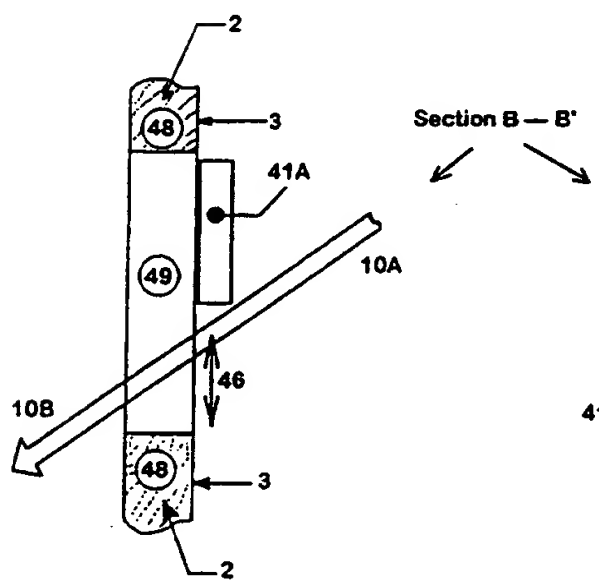


Figure 4c

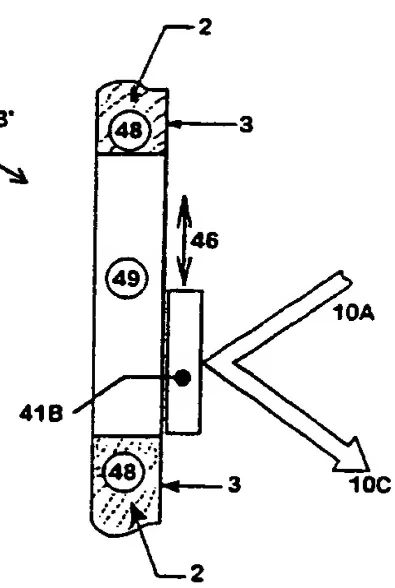


Figure 4d

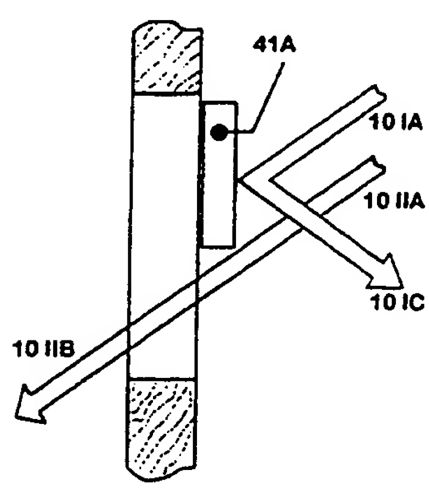


Figure 4e

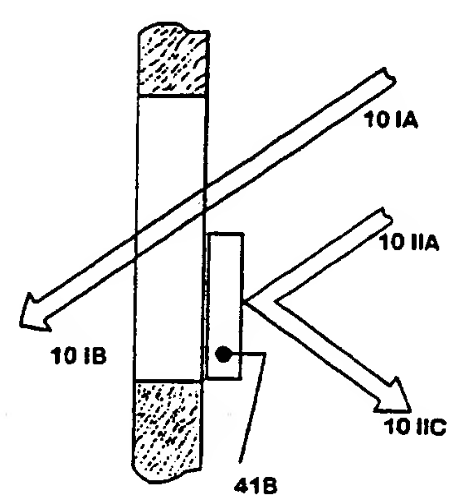


Figure 4f

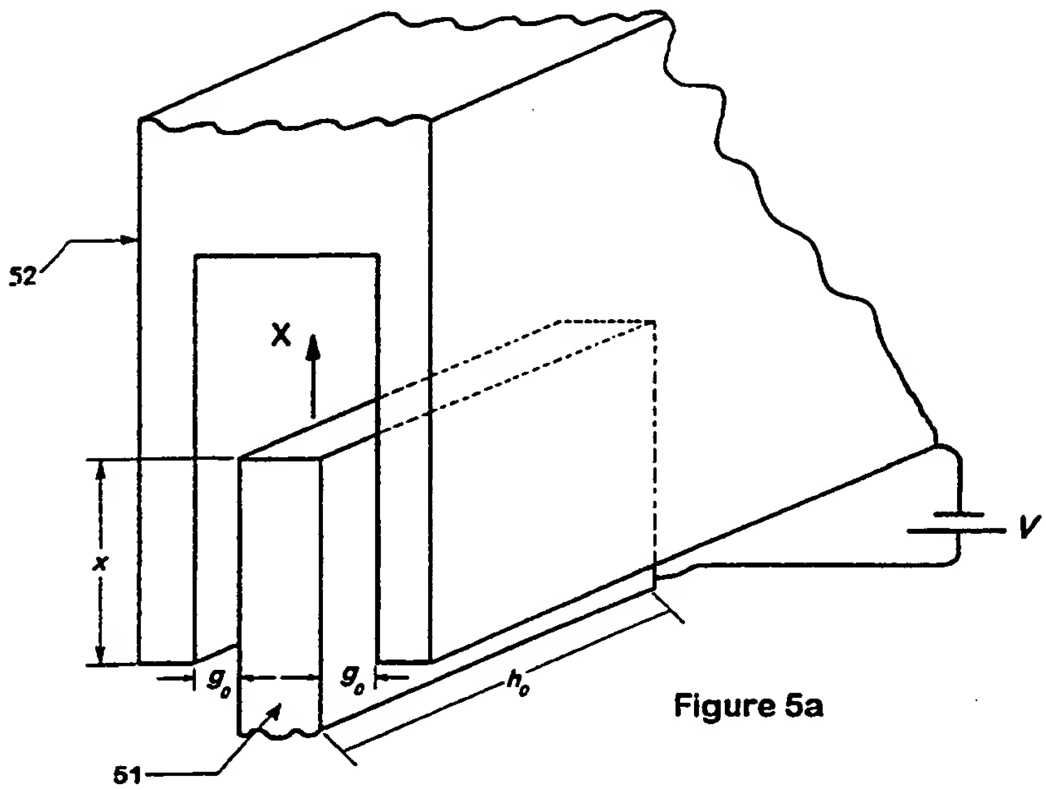


Figure 5a

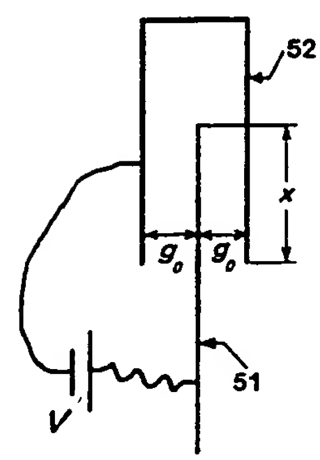


Figure 5b

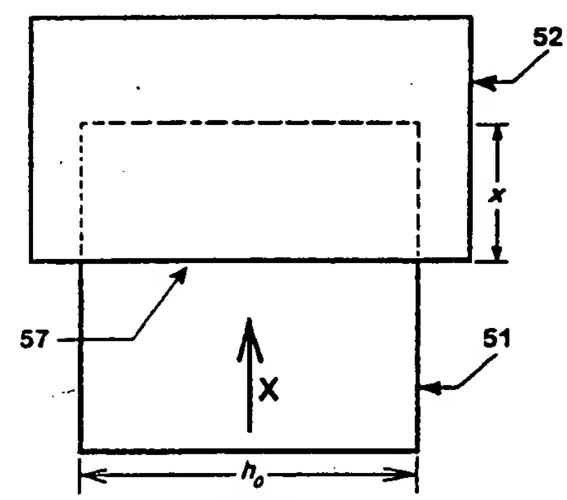


Figure 5c

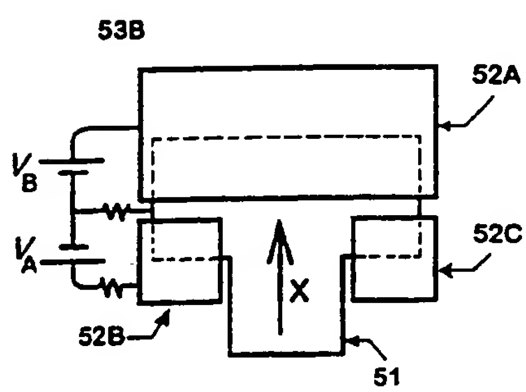


Figure 5d

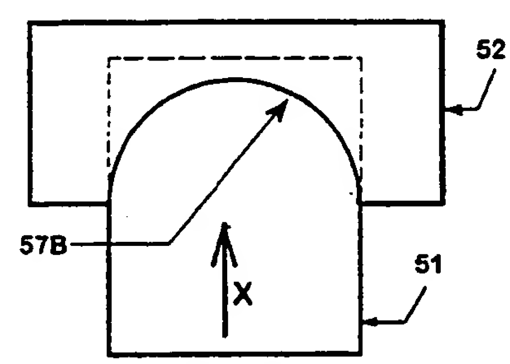


Figure 5e

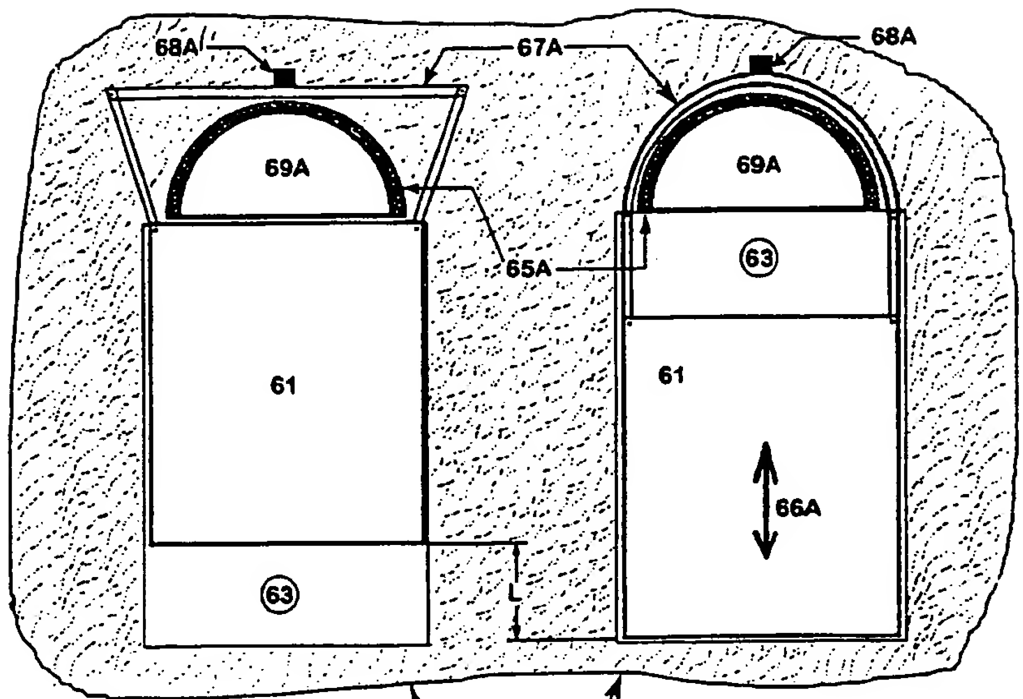


Figure 6a

Figure 6b

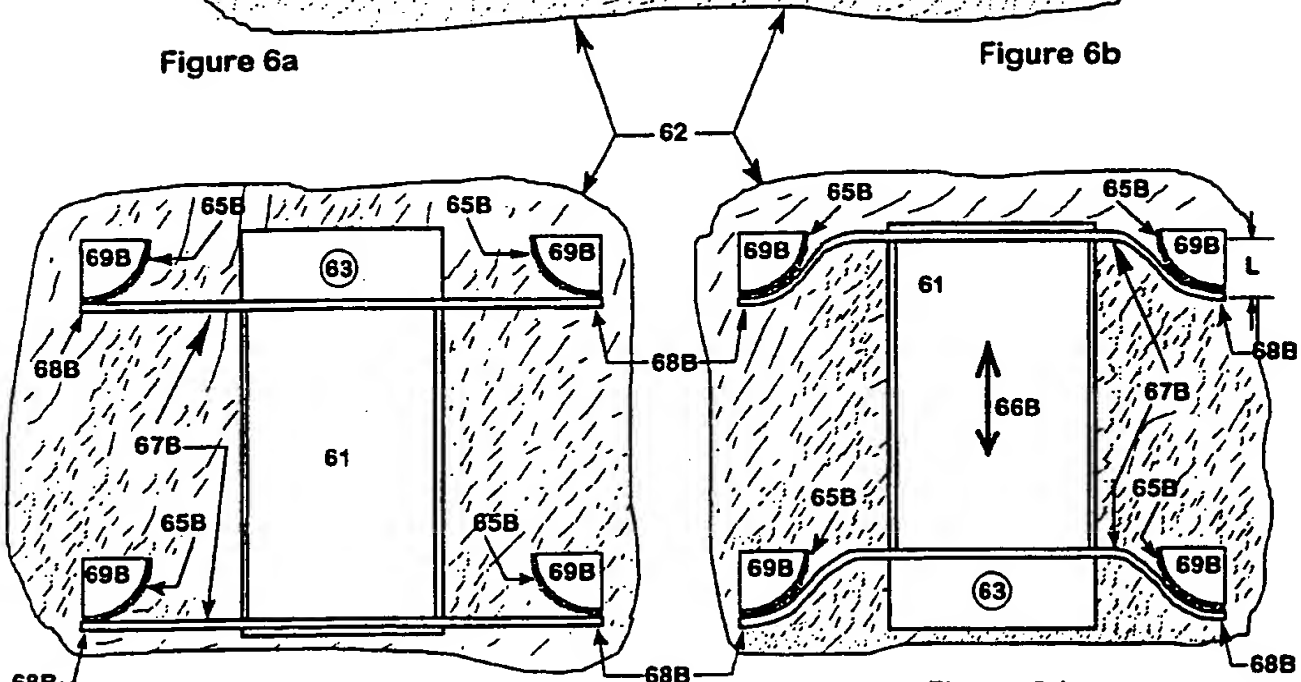


Figure 6c

Figure 6d

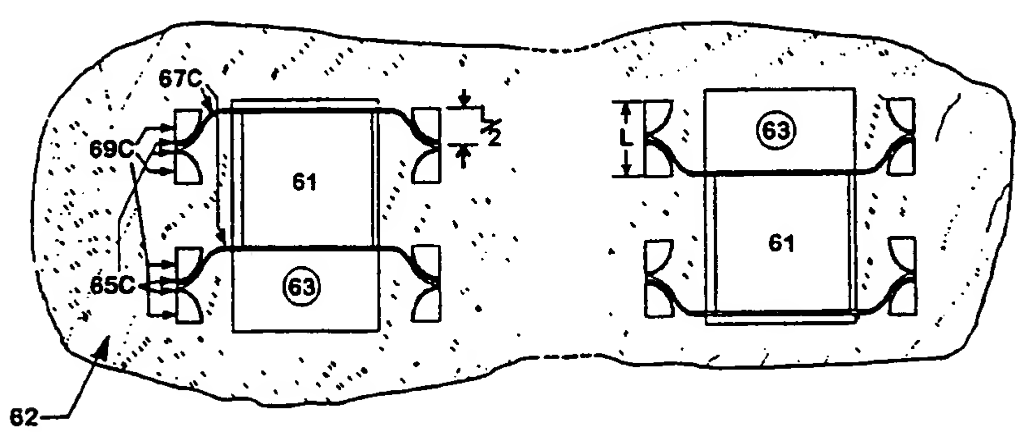


Figure 6e

Figure 6f

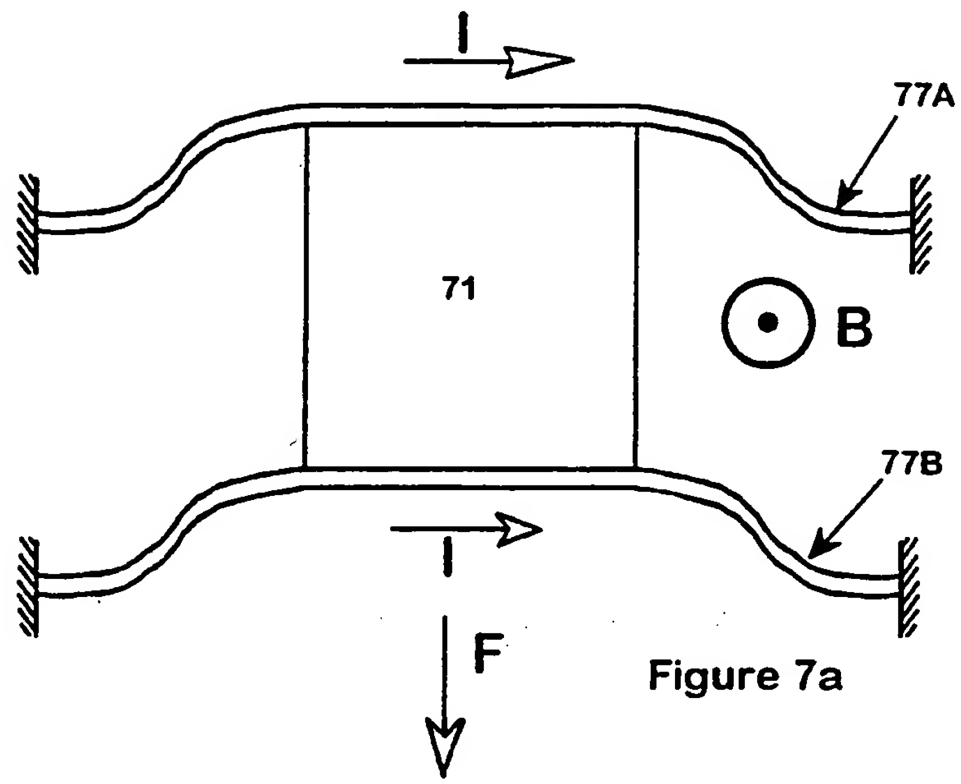


Figure 7a

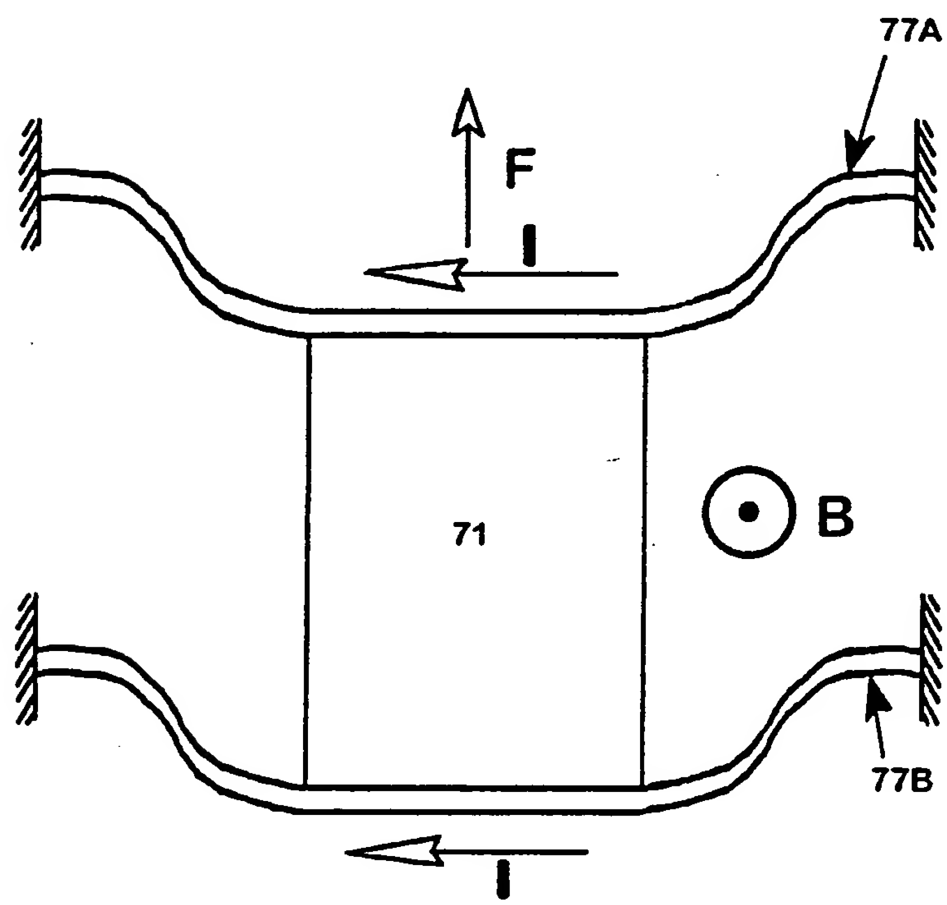


Figure 7b

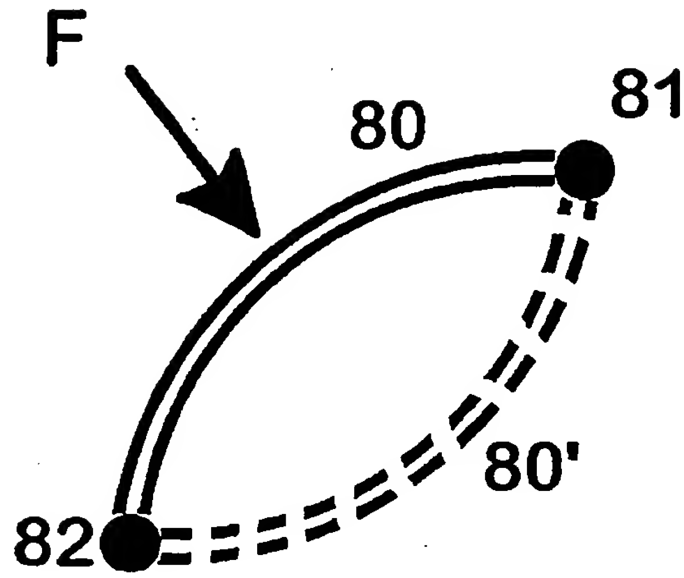


Figure 8a

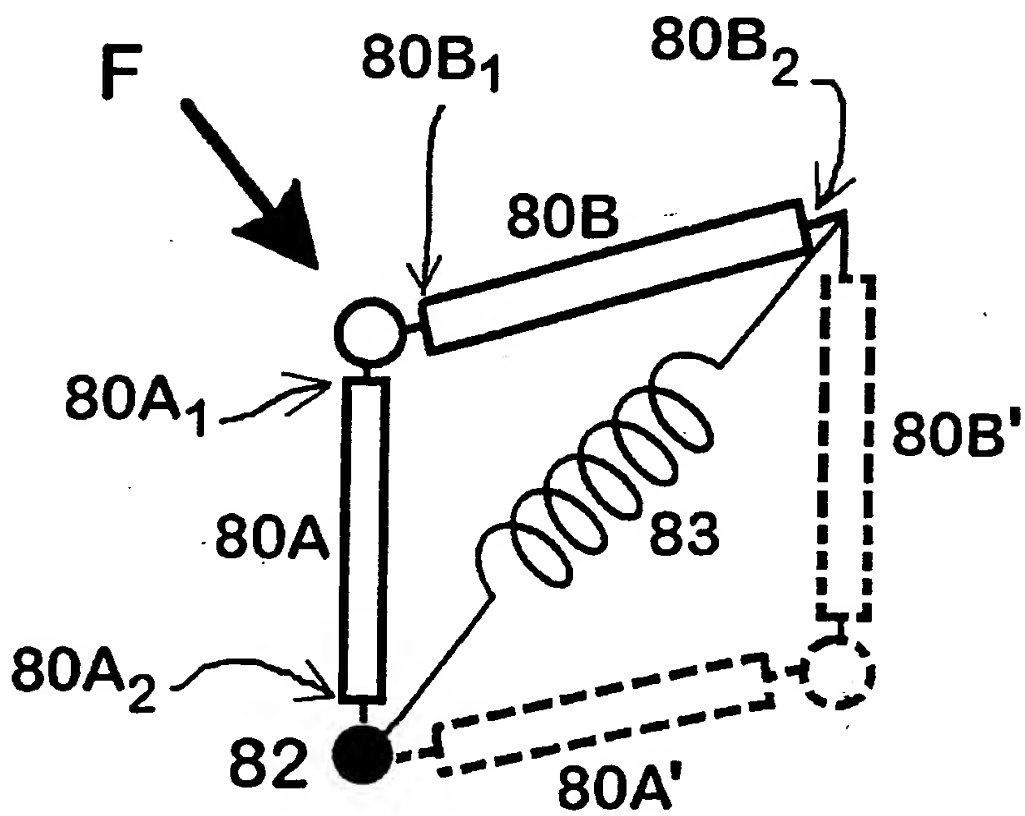


Figure 8b

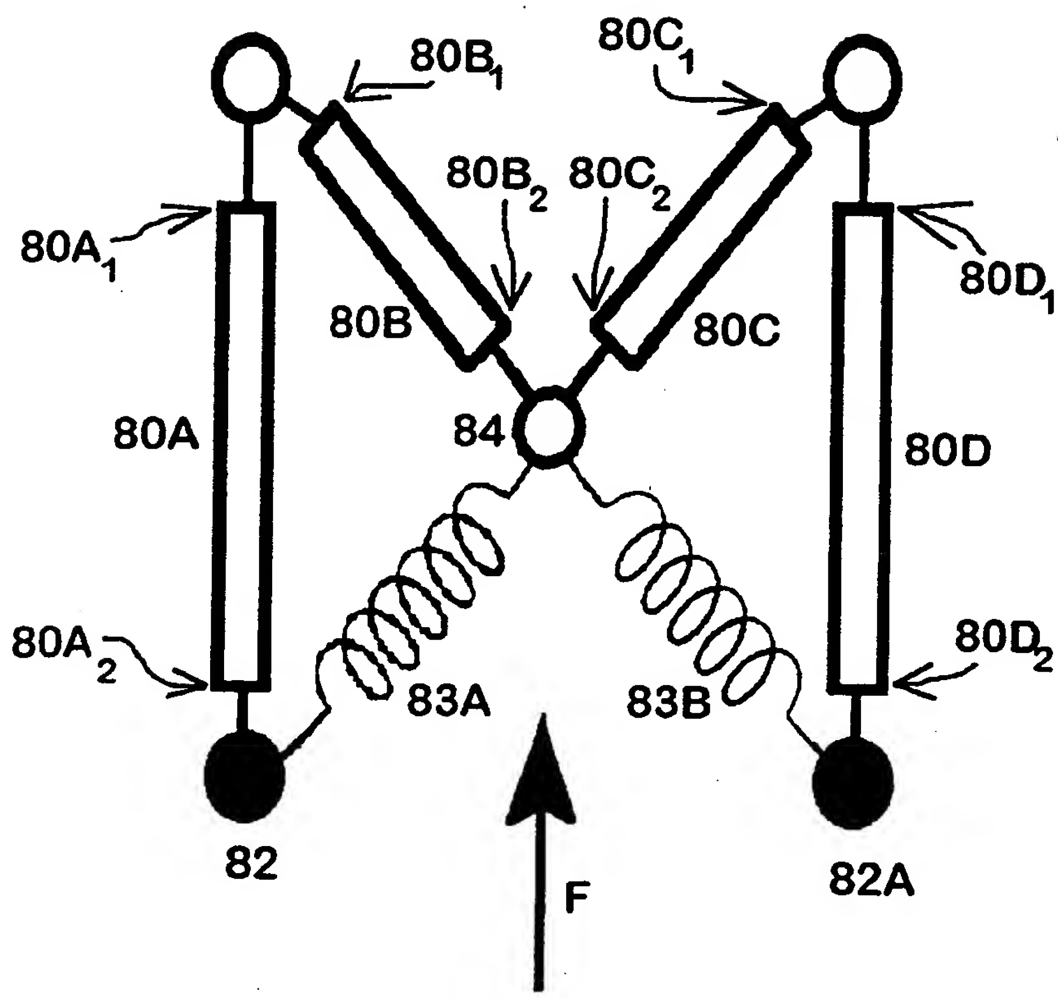


Figure 8c

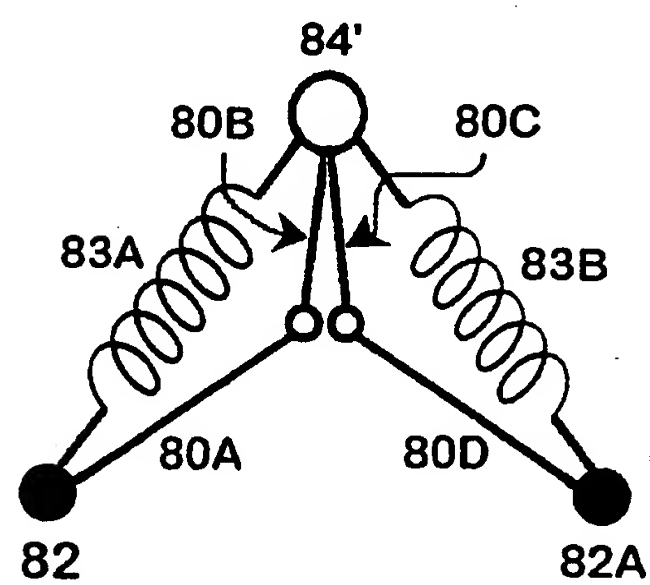


Figure 8d

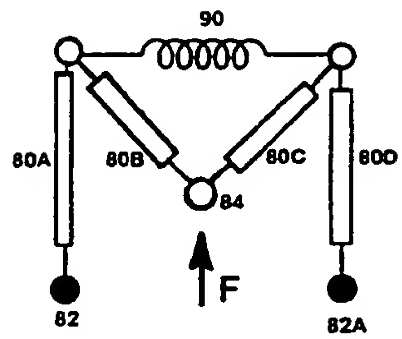


Figure 9a

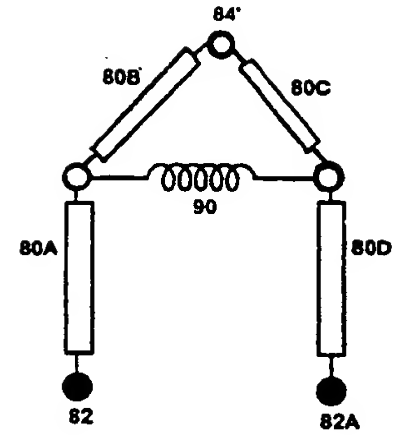


Figure 9b

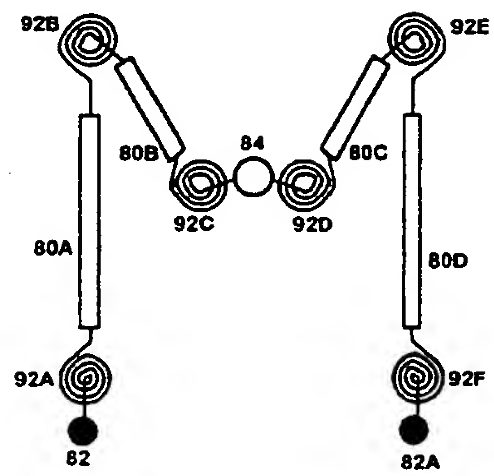


Figure 9c

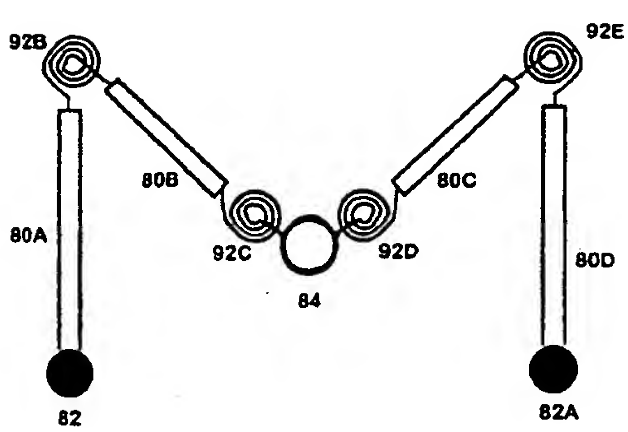


Figure 9d

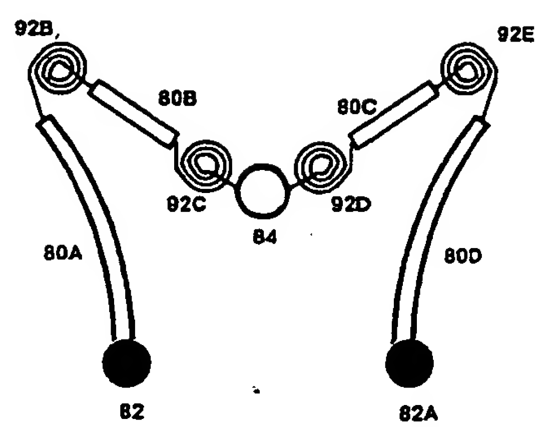


Figure 9e

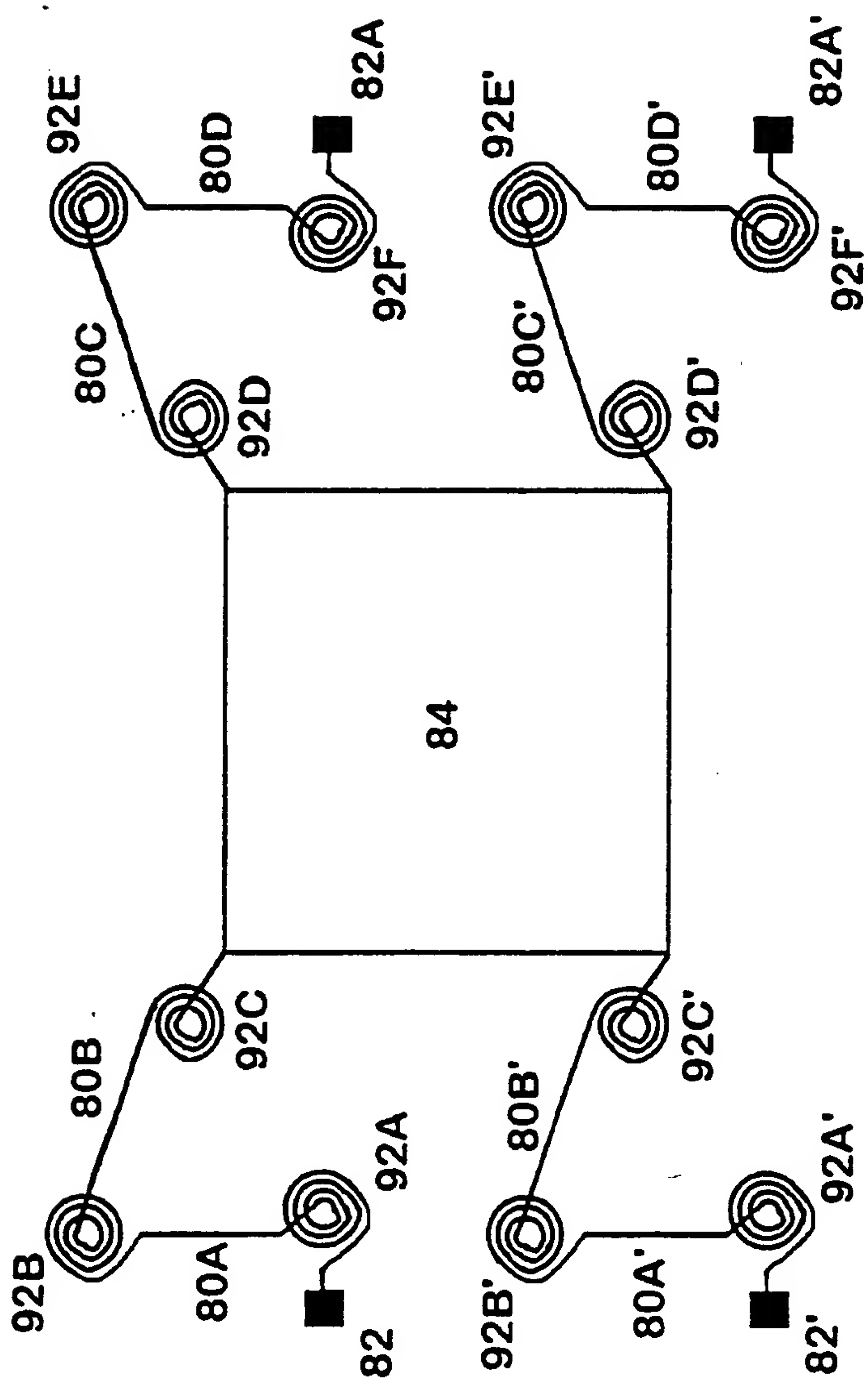

92E
80D
82A
92F
80C
92D
92E'
80D'
82A'
92F'
80C'
92D'
84
92B
80A
82
92A
80B
92C
92B'
80A'
82'
92A'
80B'
92C'

Figure 10

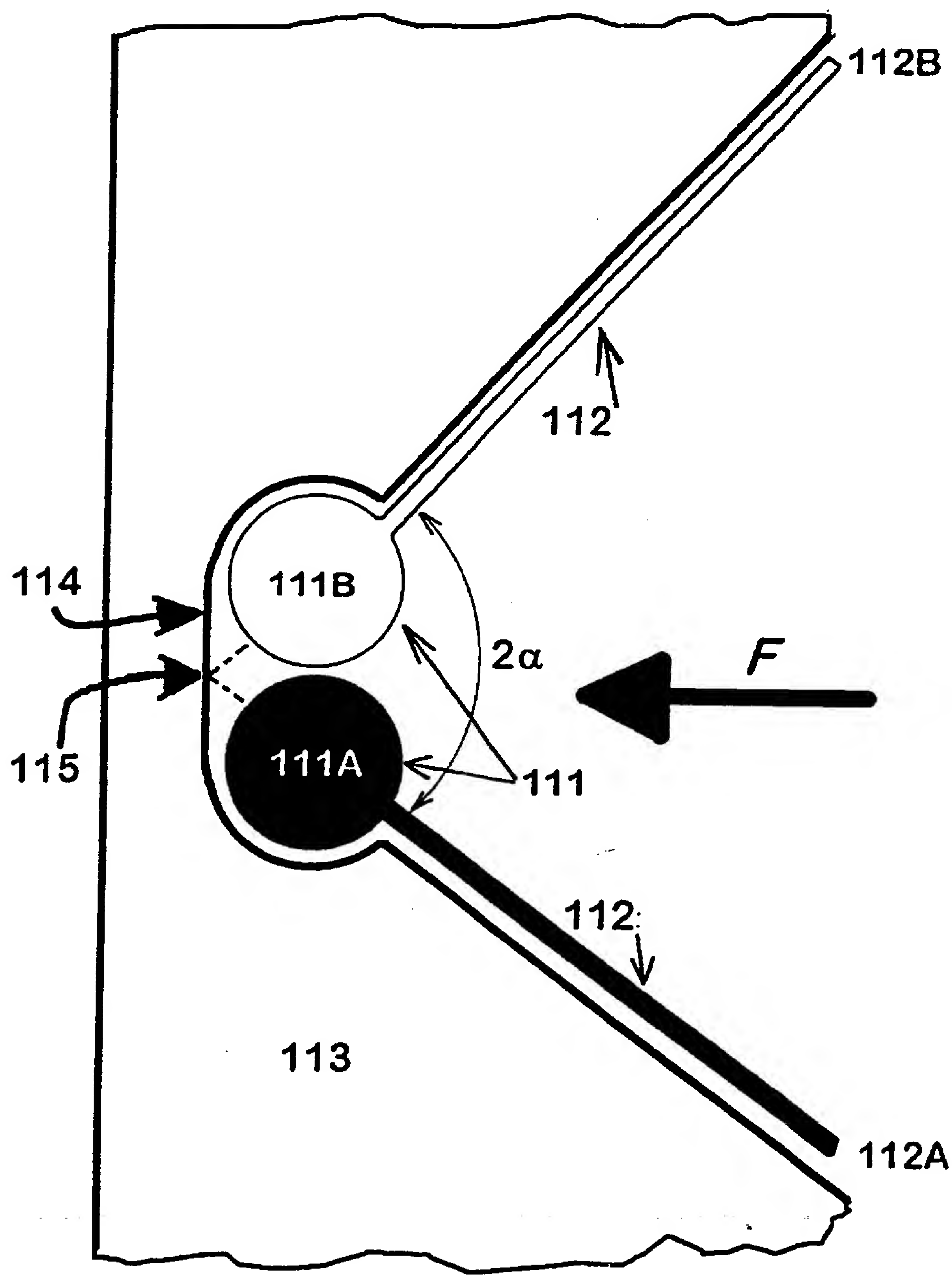


Figure 11

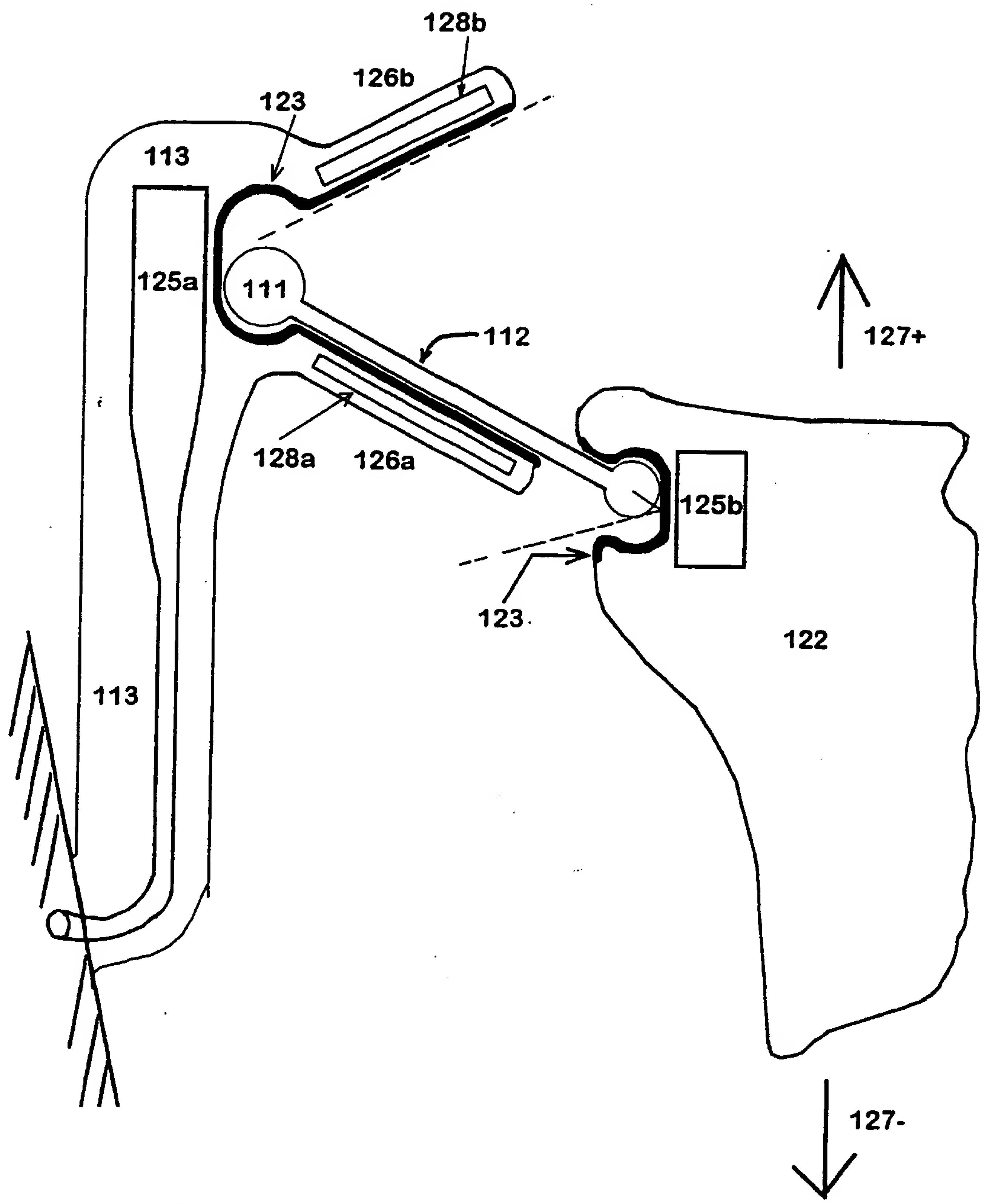

128b
126b
123
113
125a
111
112
127+
128a
126a
125b
123
122
113
127-

Figure 12

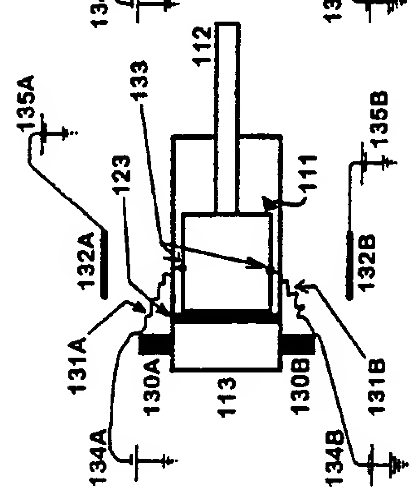


Figure 13a

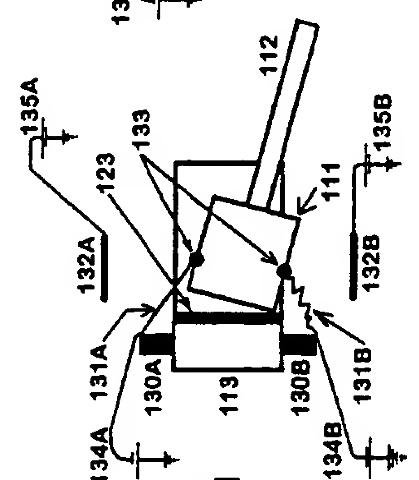


Figure 13b

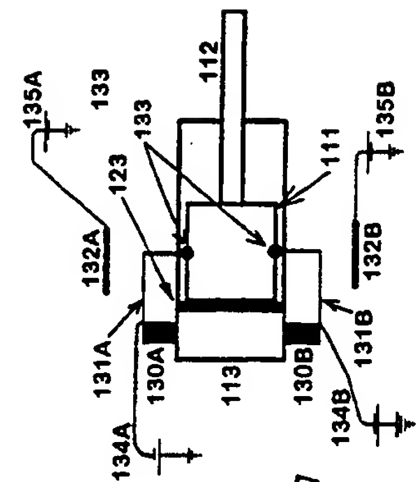


Figure 13c

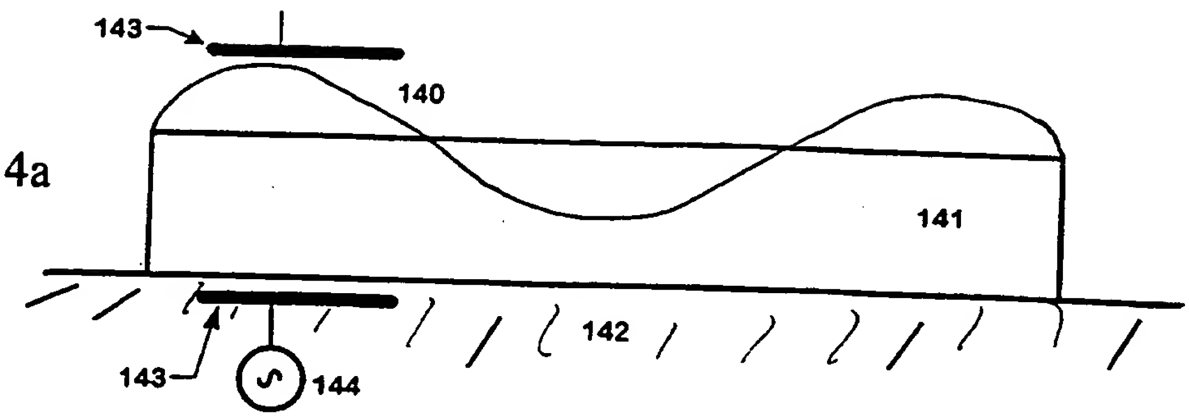


Figure 14a

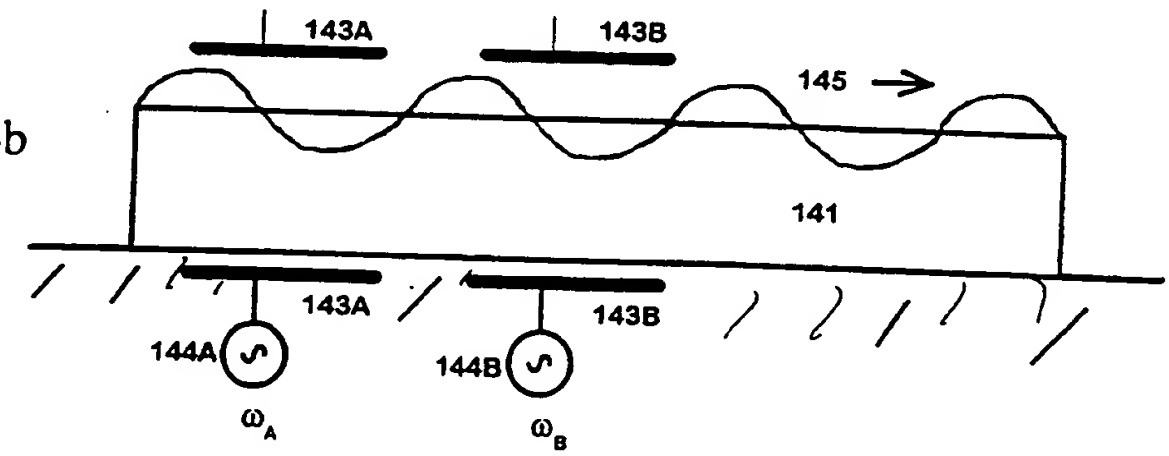


Figure 14b

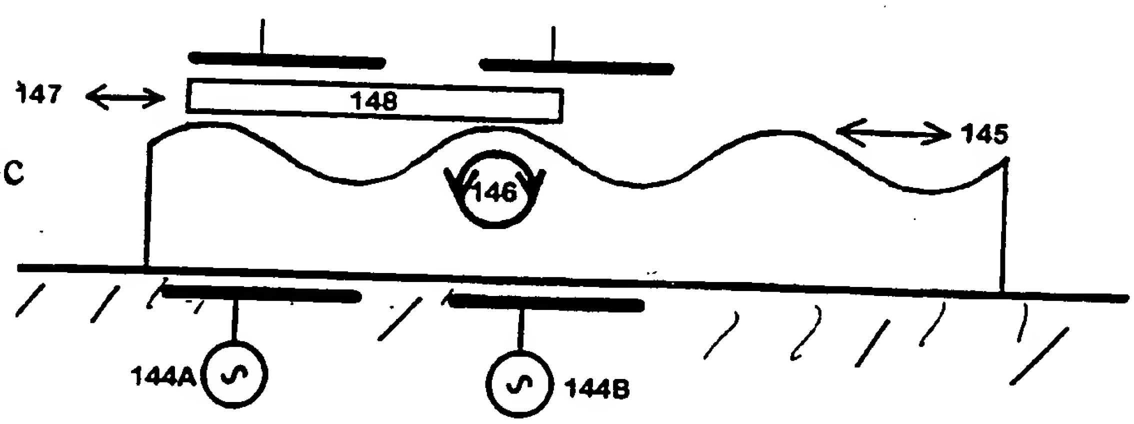


Figure 14c

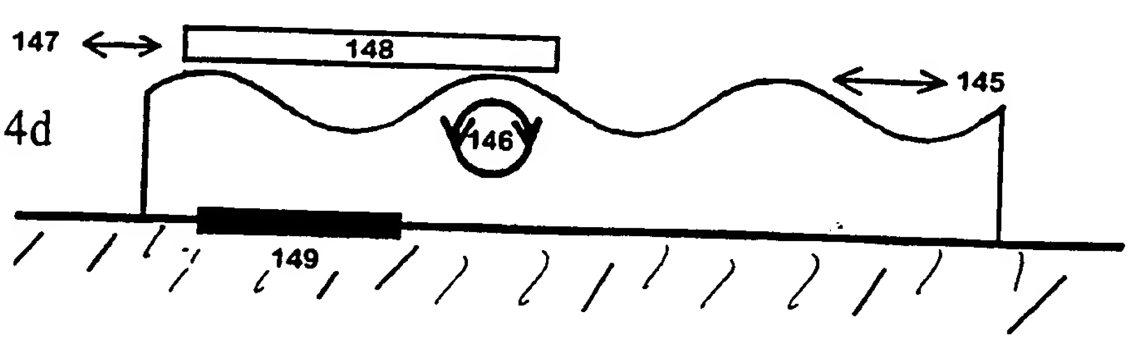


Figure 14d

Figure 15a

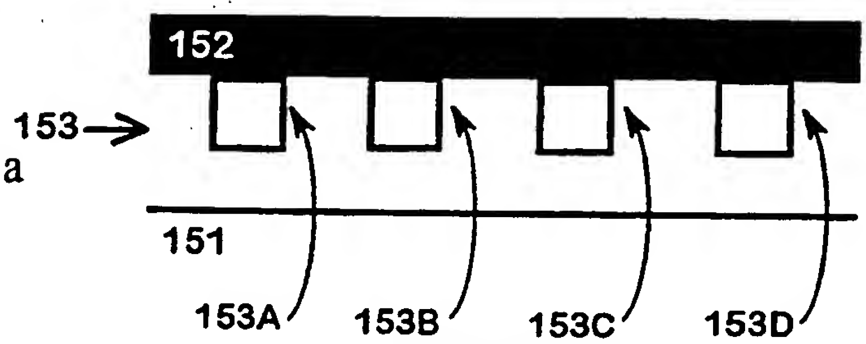


Figure 15b

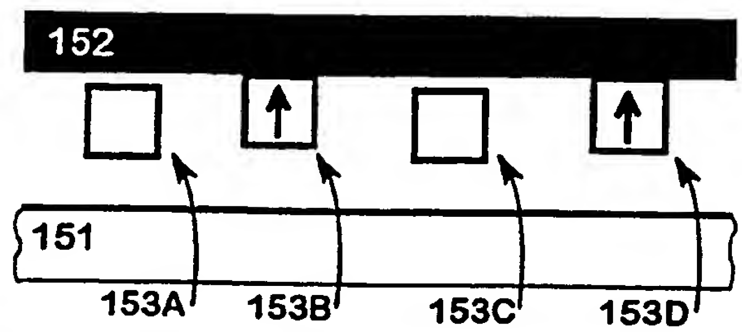


Figure 15c

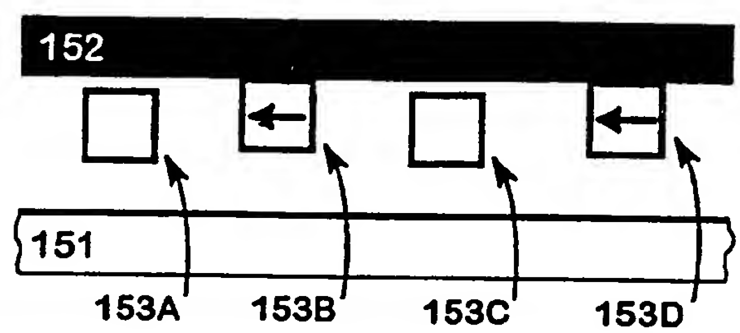


Figure 15d

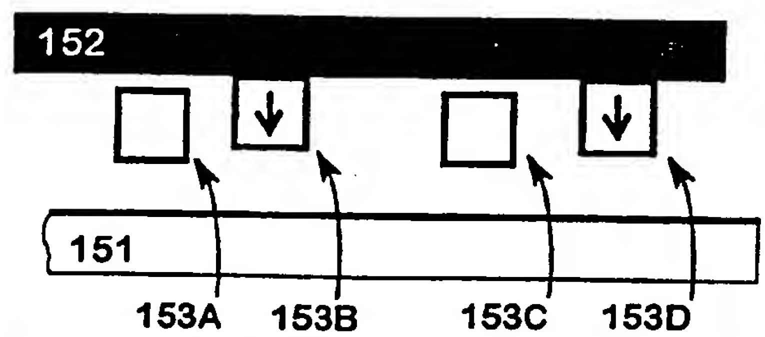


Figure 15e

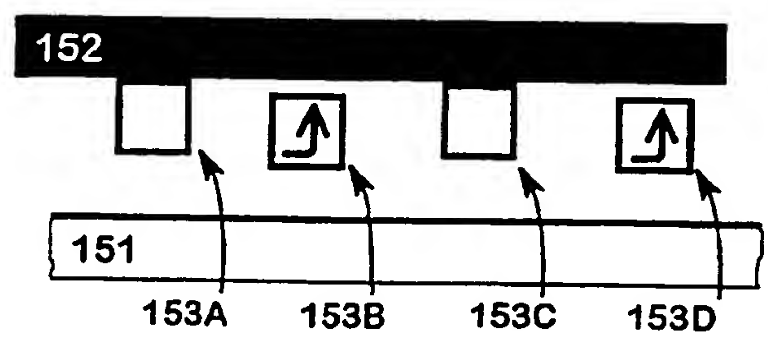


Figure 16a

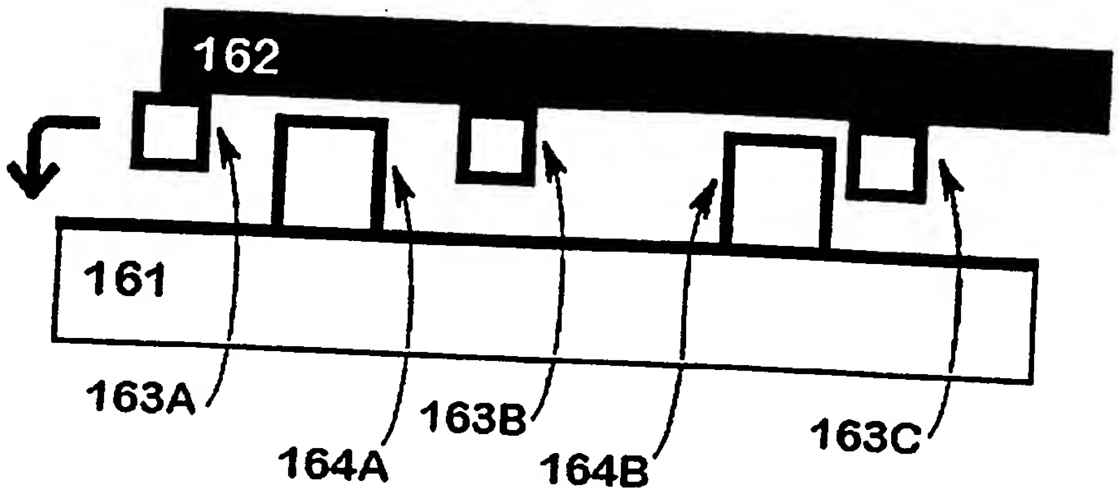
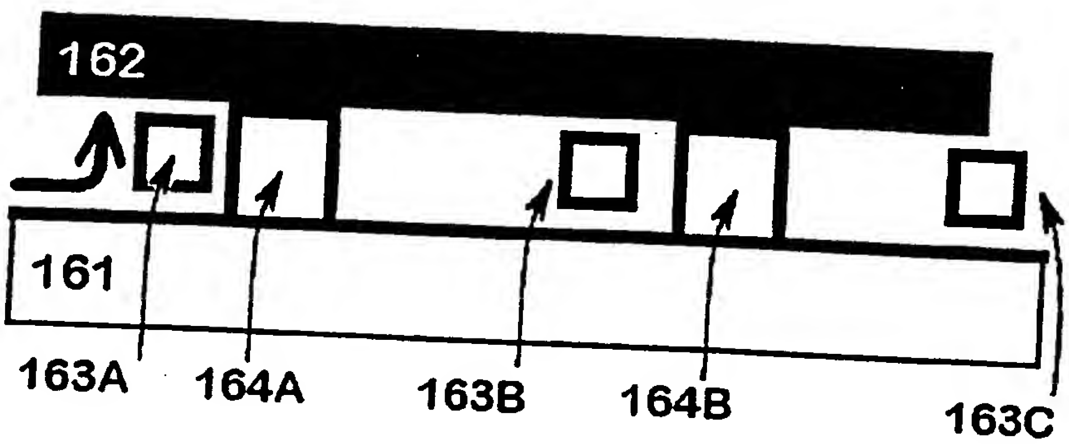


Figure 16b



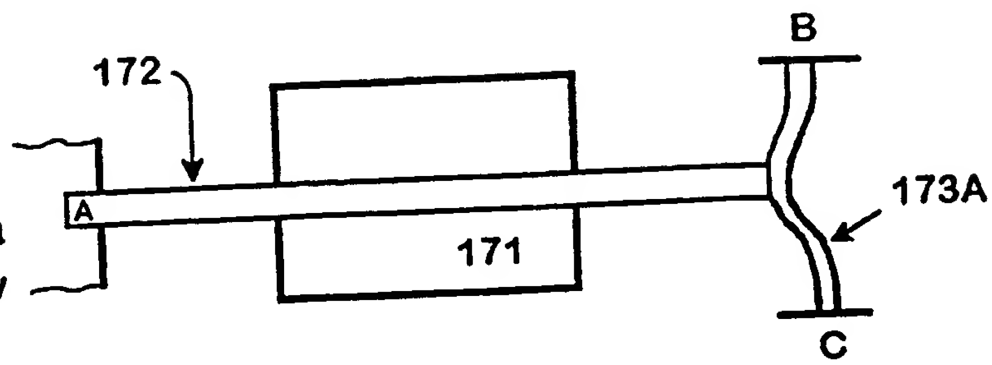


Figure 17a
Plan view

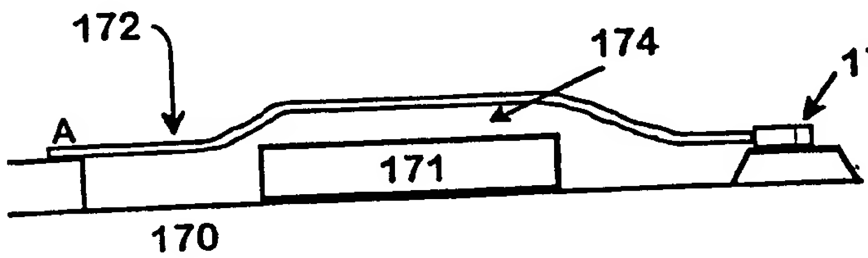


Figure 17b
Side elevation

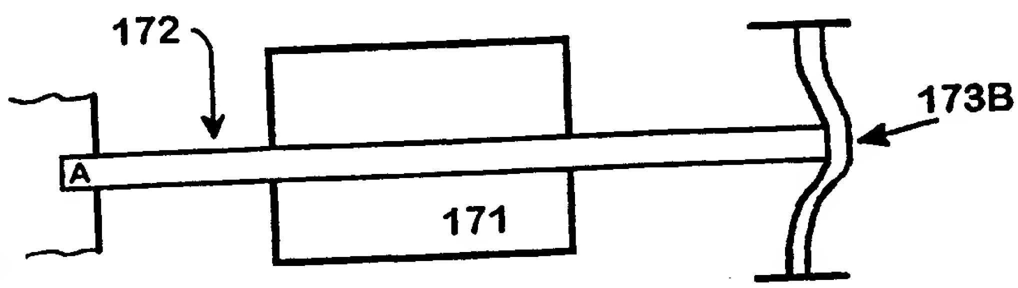


Figure 17c
Plan view

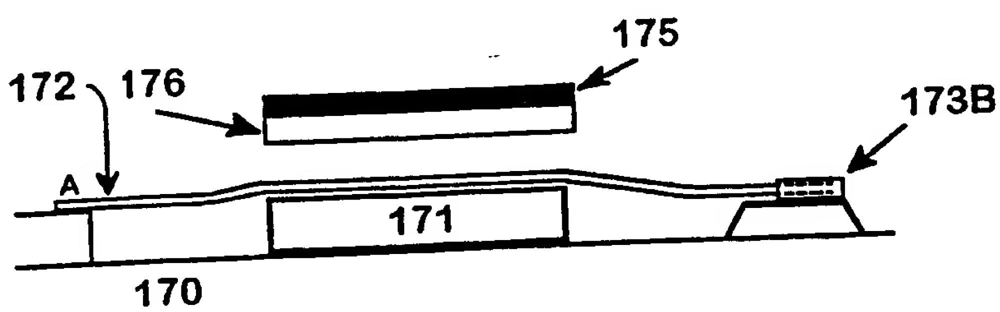


Figure 17d
Side elevation

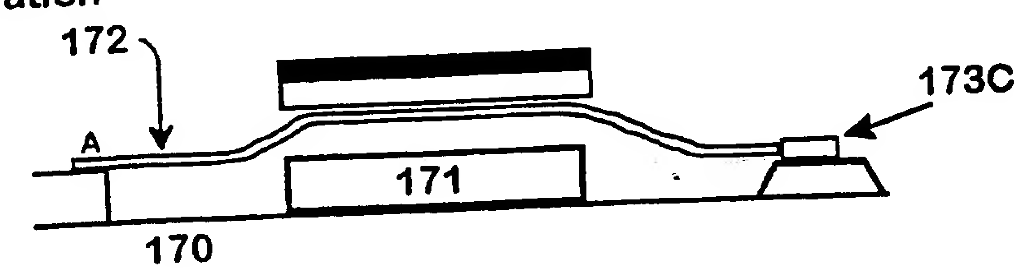


Figure 17e
Side elevation

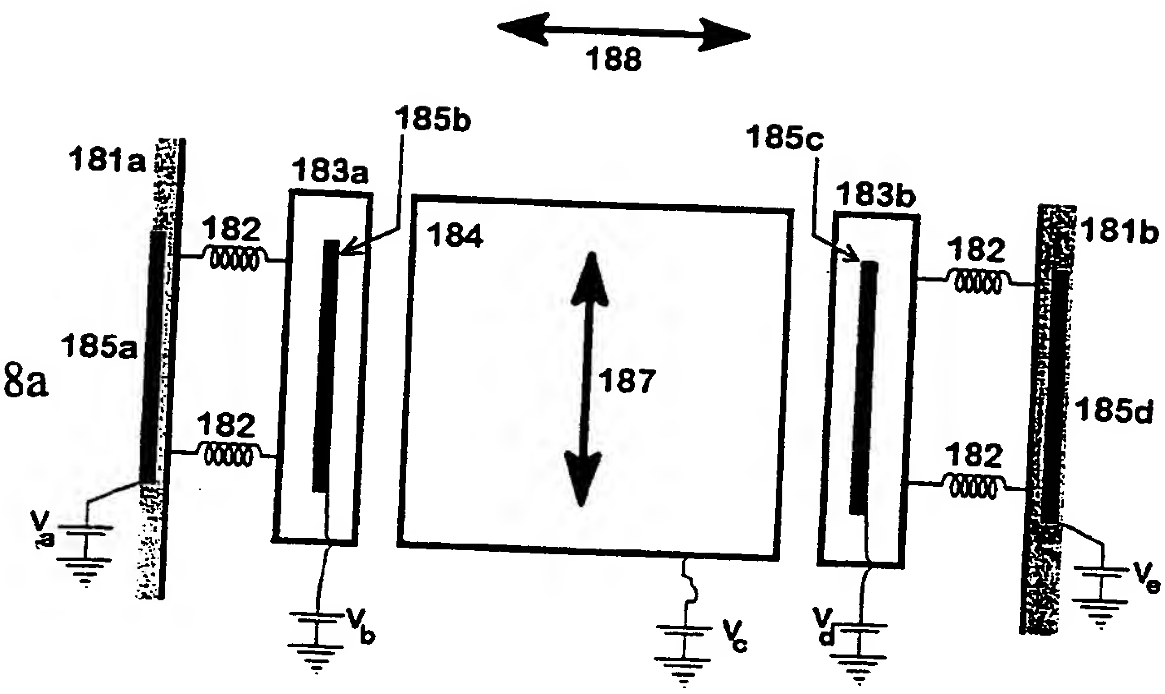


Figure 18a

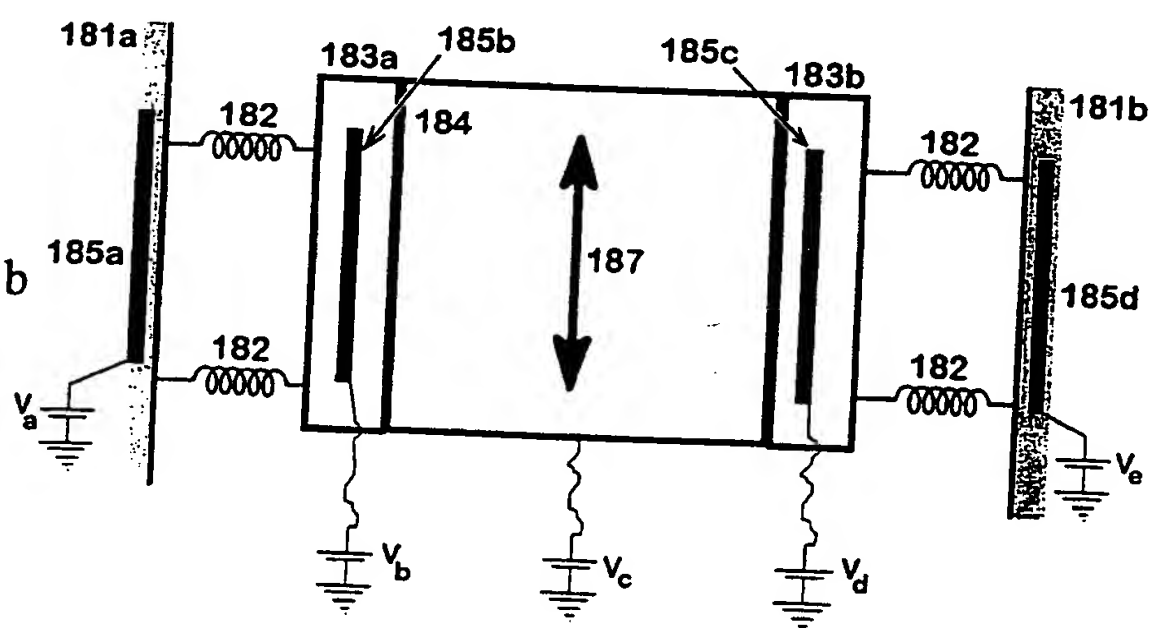


Figure 18b

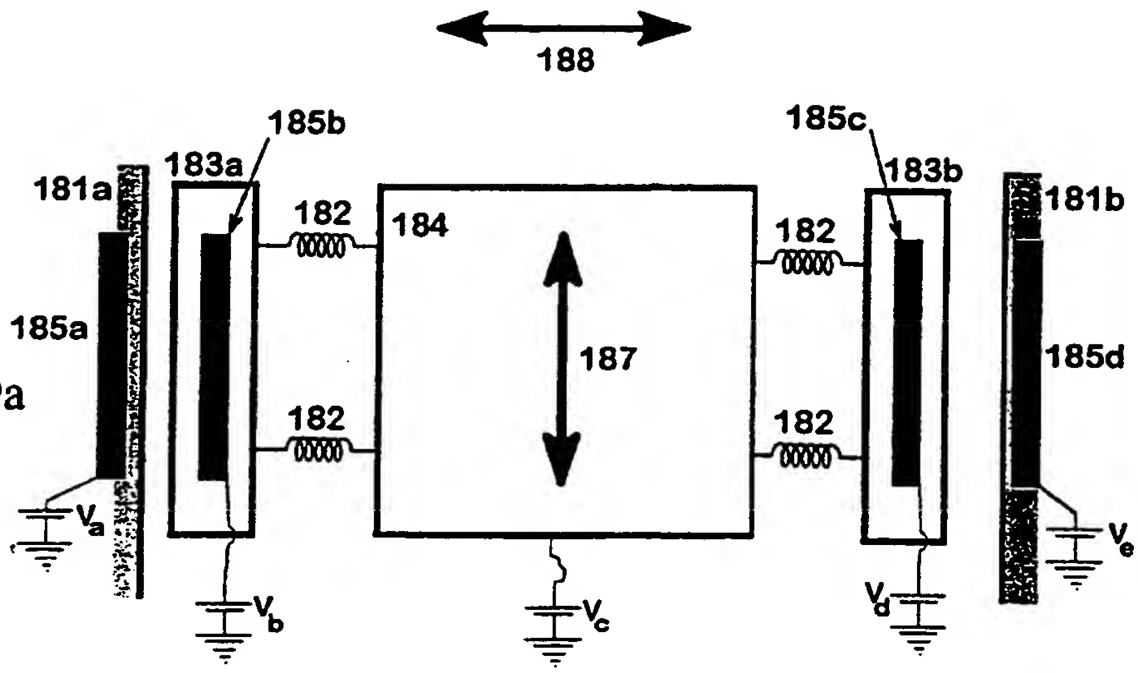


Figure 19a

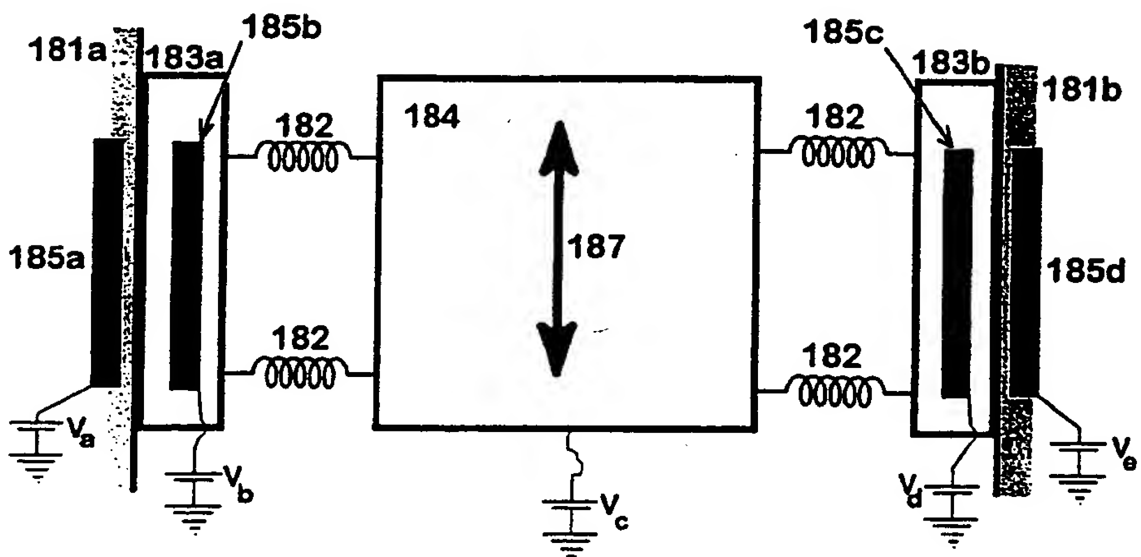


Figure 19b

Figure 20a

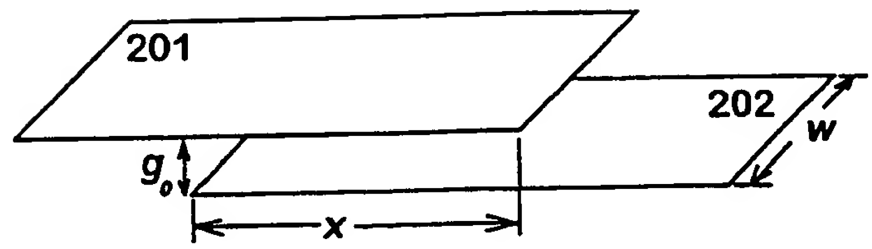


Figure 20b

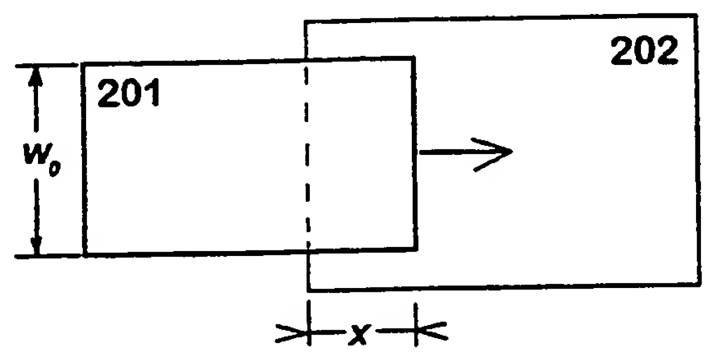


Figure 20c

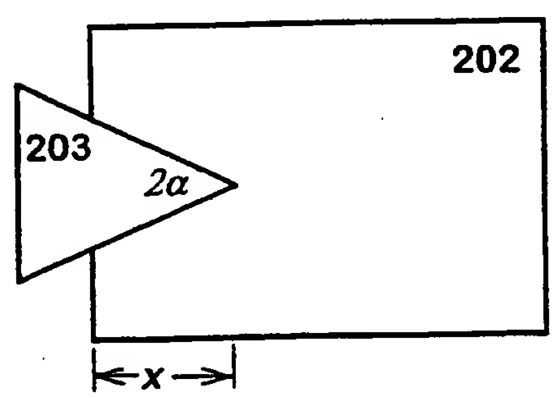
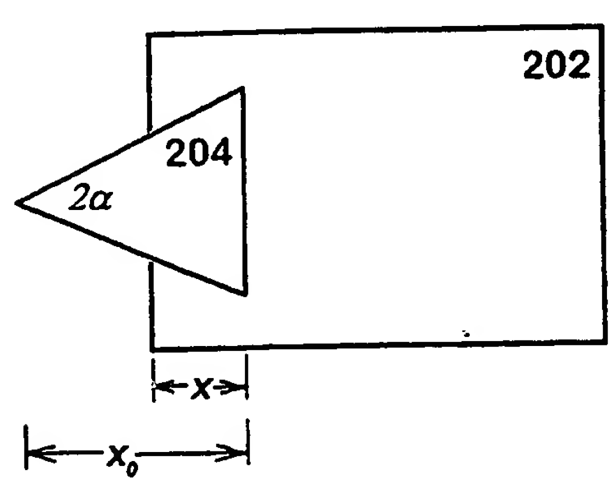


Figure 20d



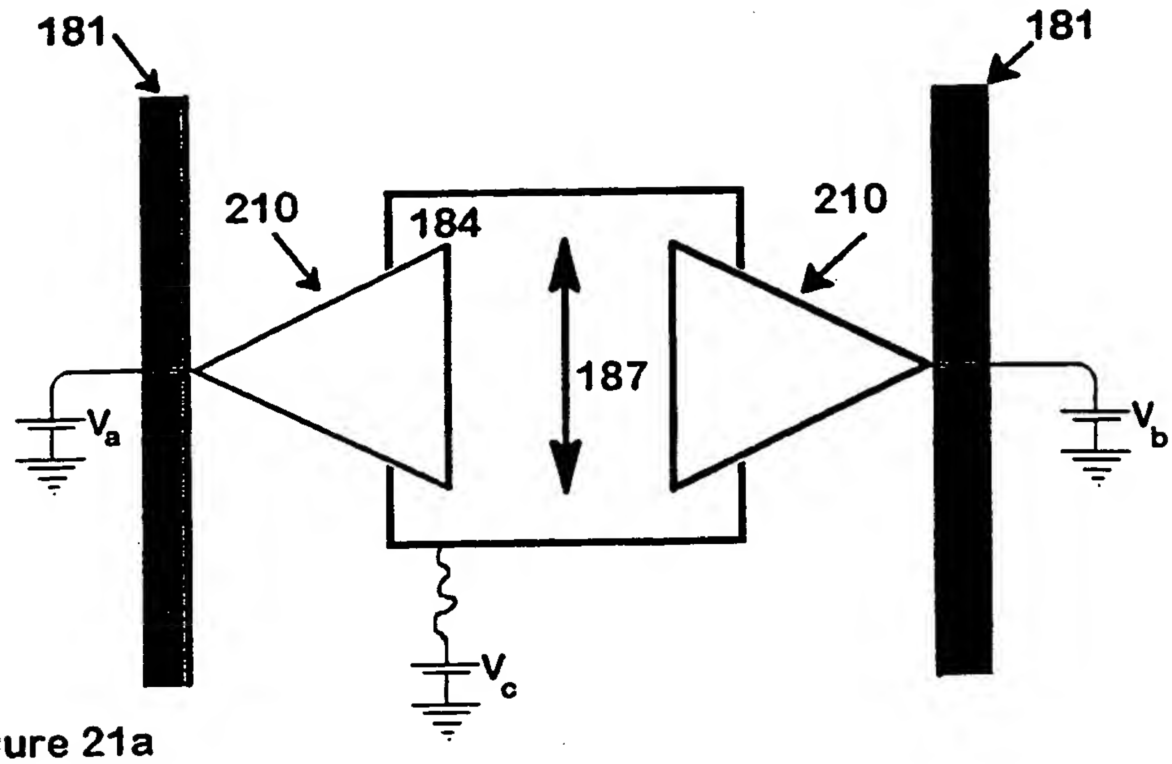


Figure 21a

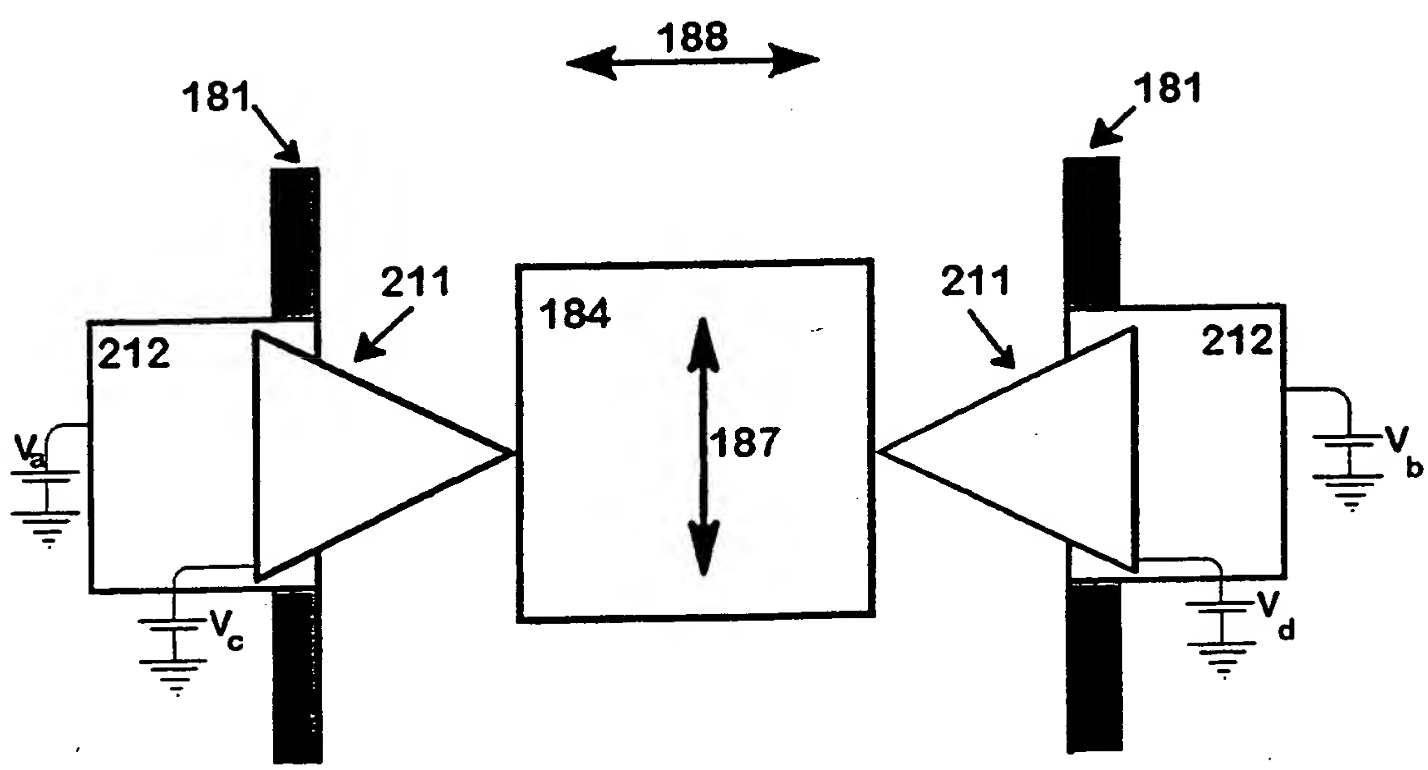


Figure 21b

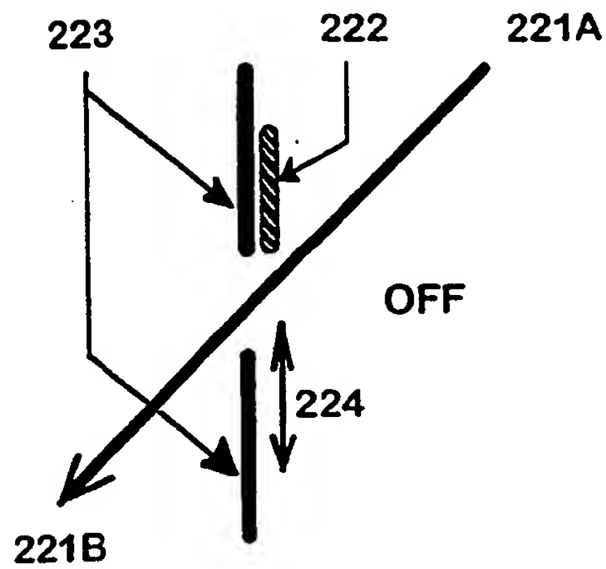


Figure 22a

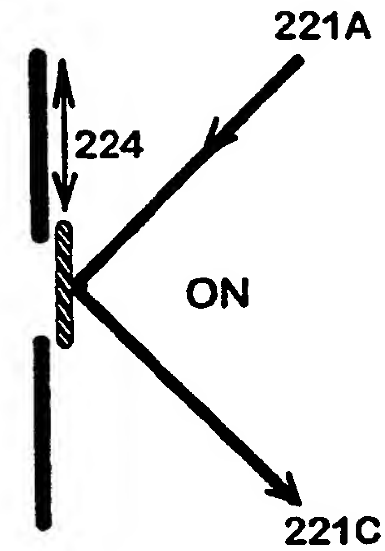


Figure 22b

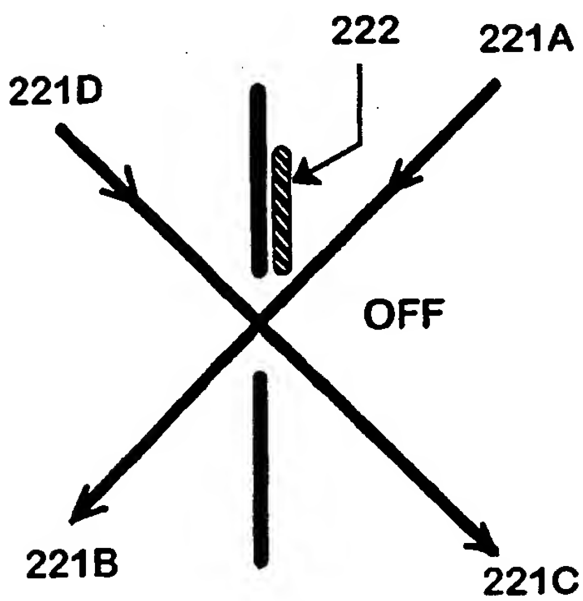


Figure 22c

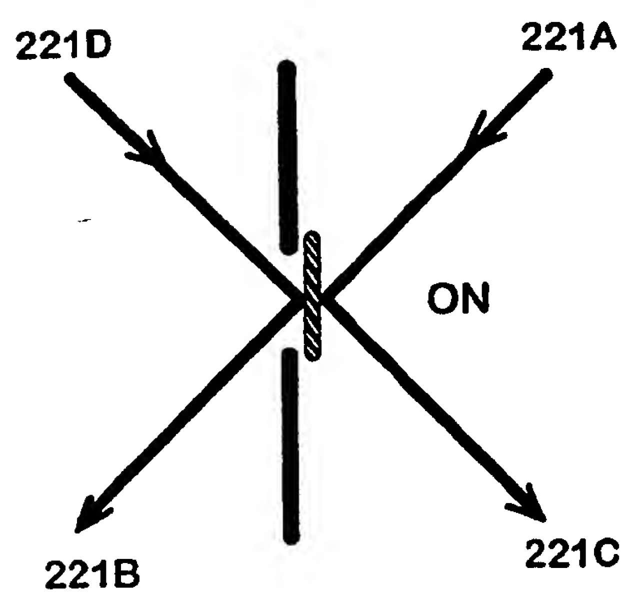


Figure 22d

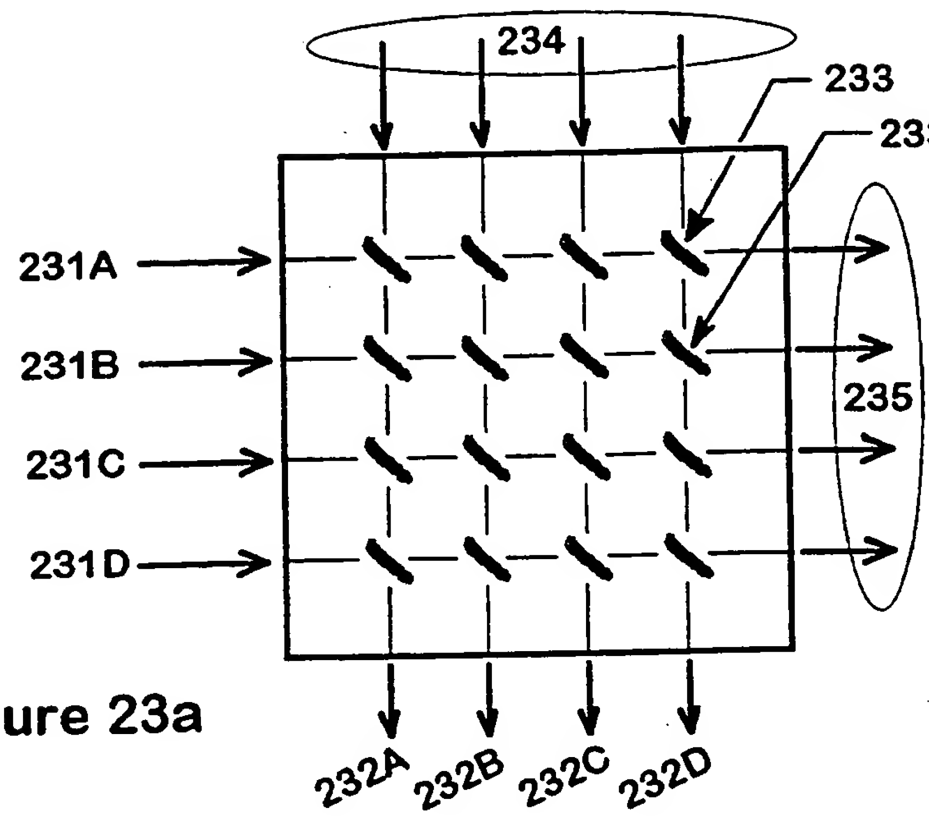


Figure 23a

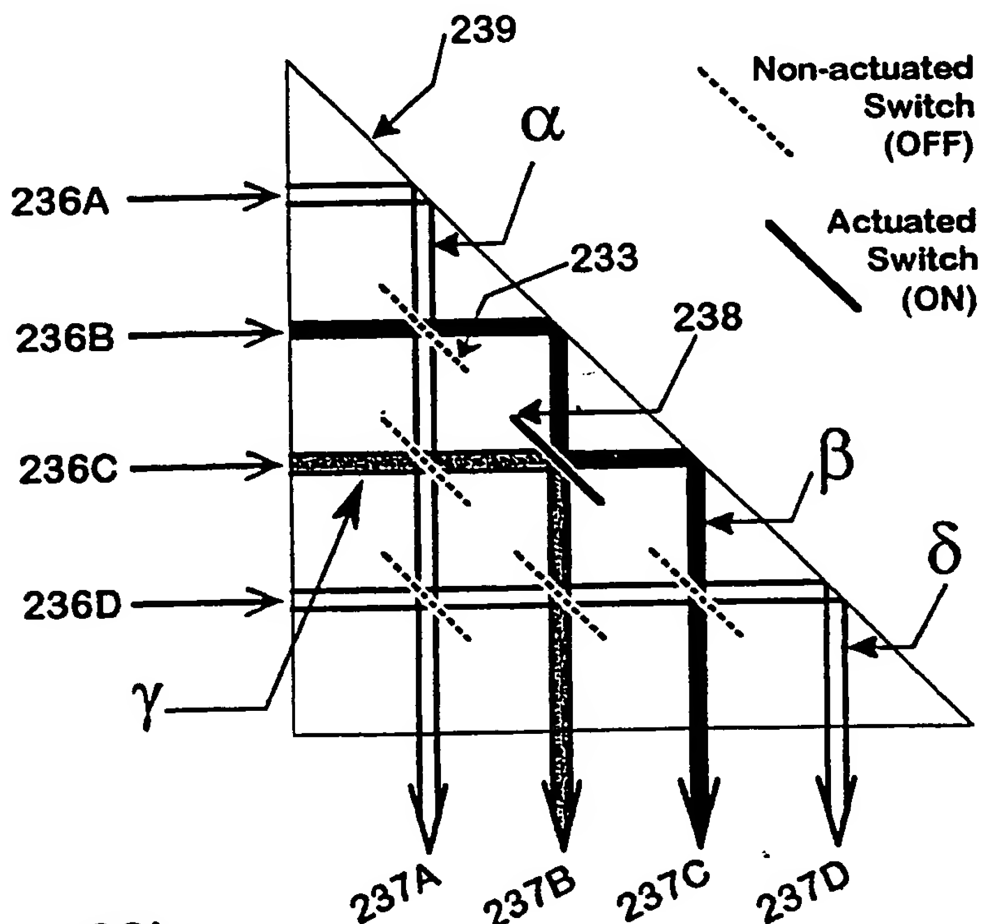


Figure 23b

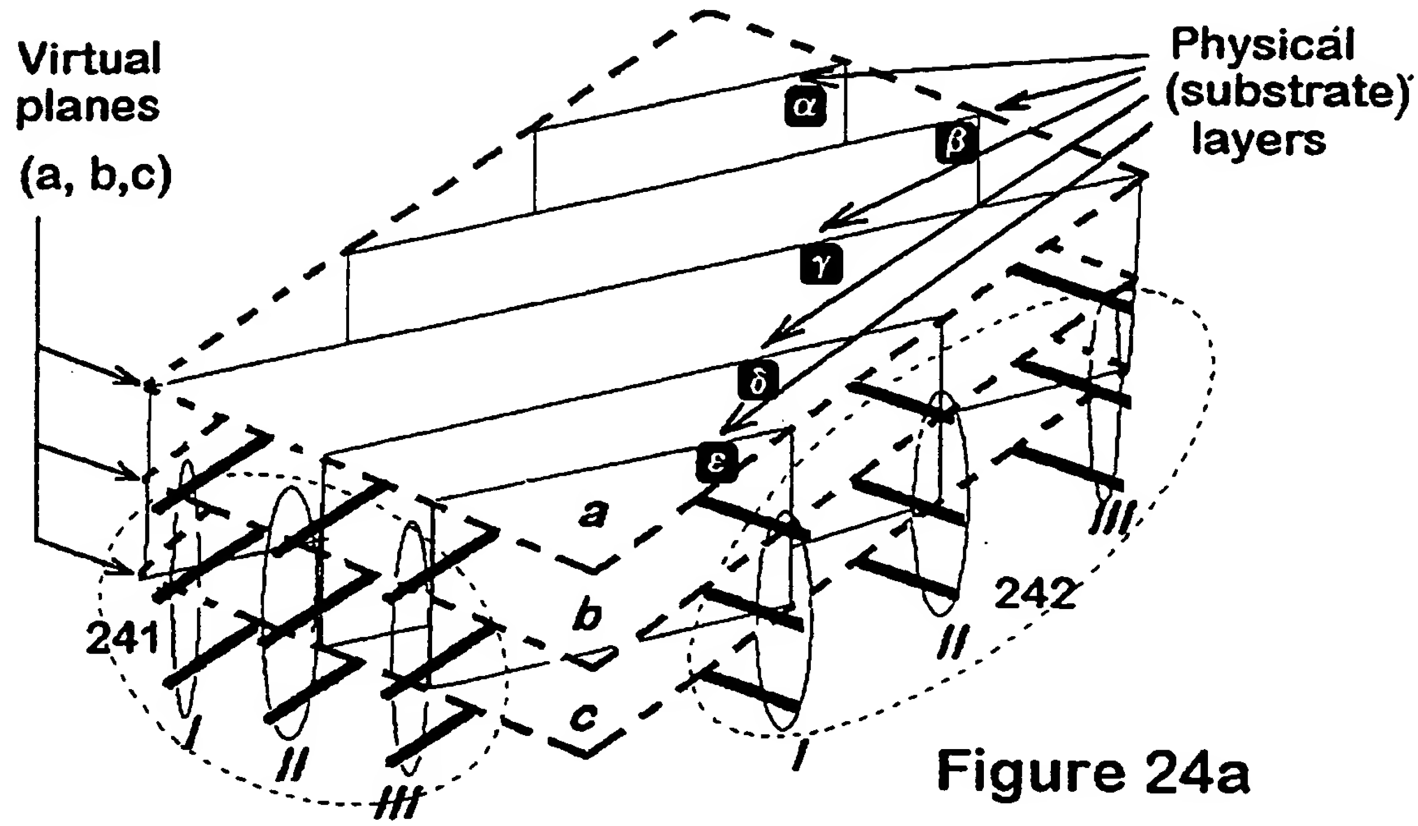
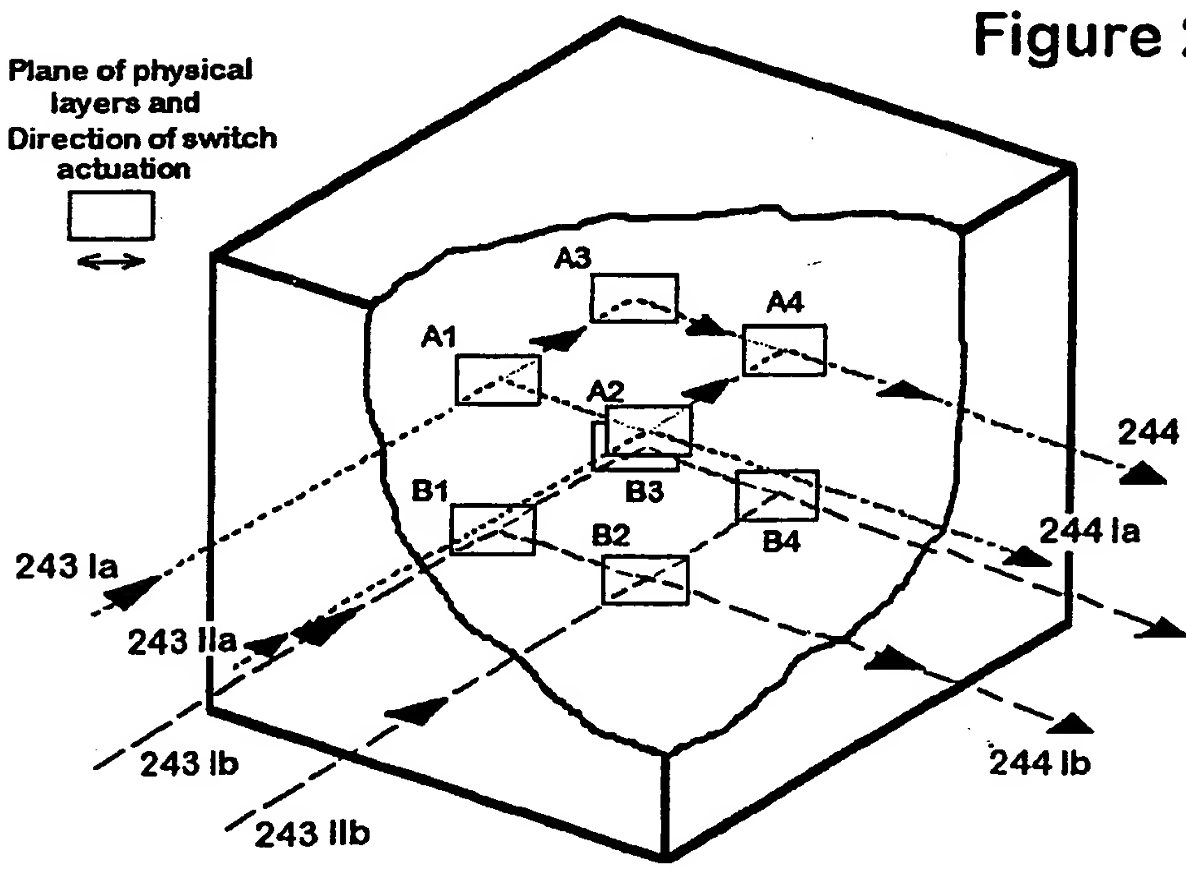


Figure 24a

Figure 24b



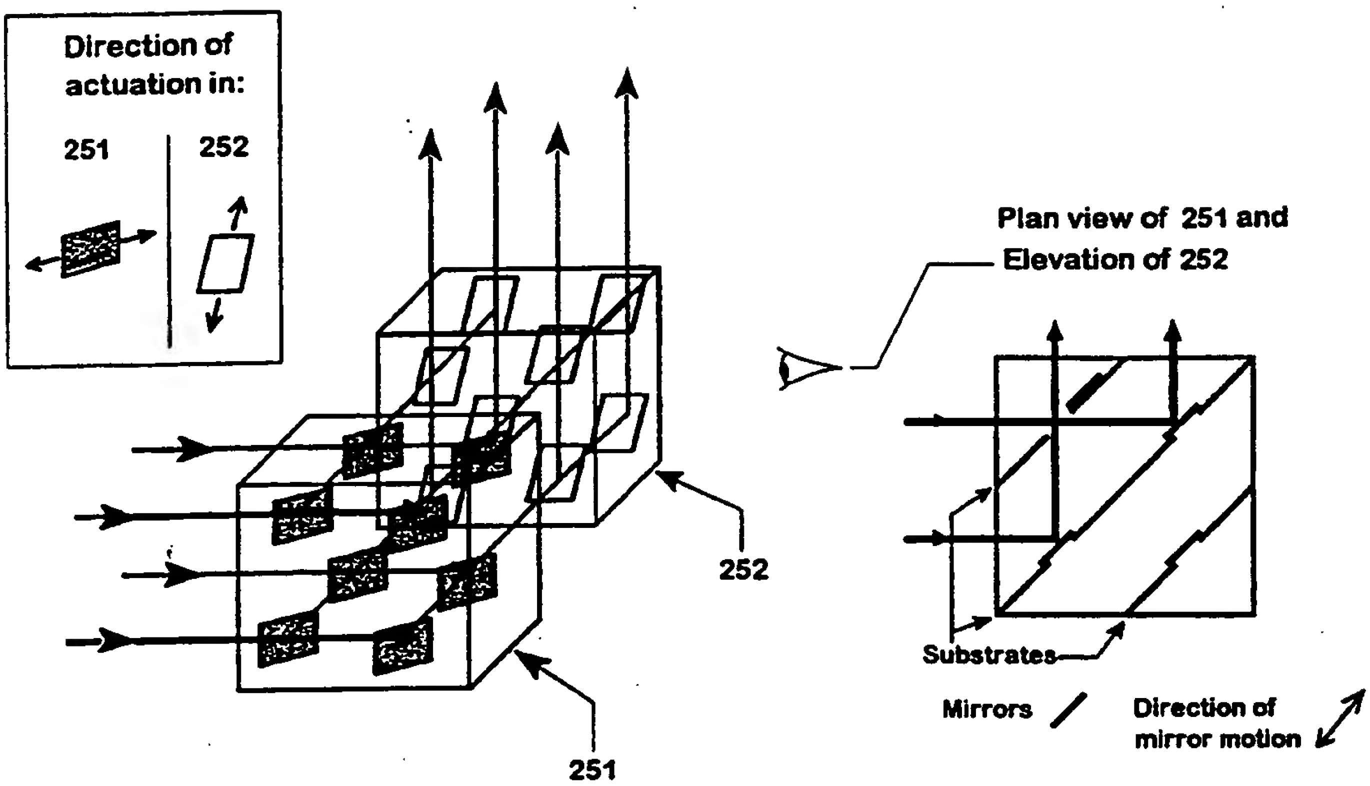

Direction of
actuation in:
251
252
Plan view of 251 and
Elevation of 252
252
251
Substrates
Mirrors
Direction of
mirror motion

Figure 25a

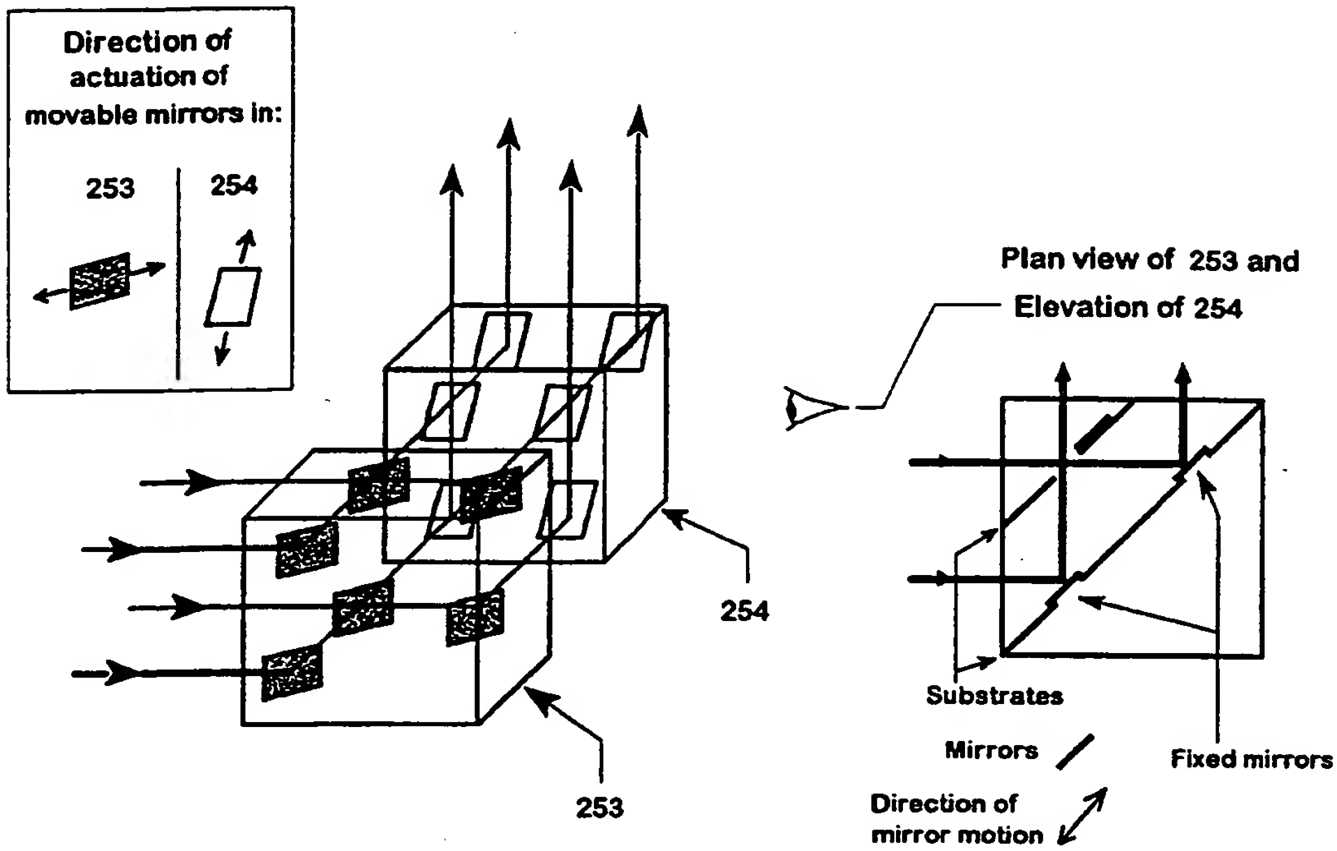

Direction of actuation of movable mirrors in:
253
254
Plan view of 253 and
Elevation of 254
254
253
Substrates
Mirrors
Fixed mirrors
Direction of mirror motion

Figure 25b

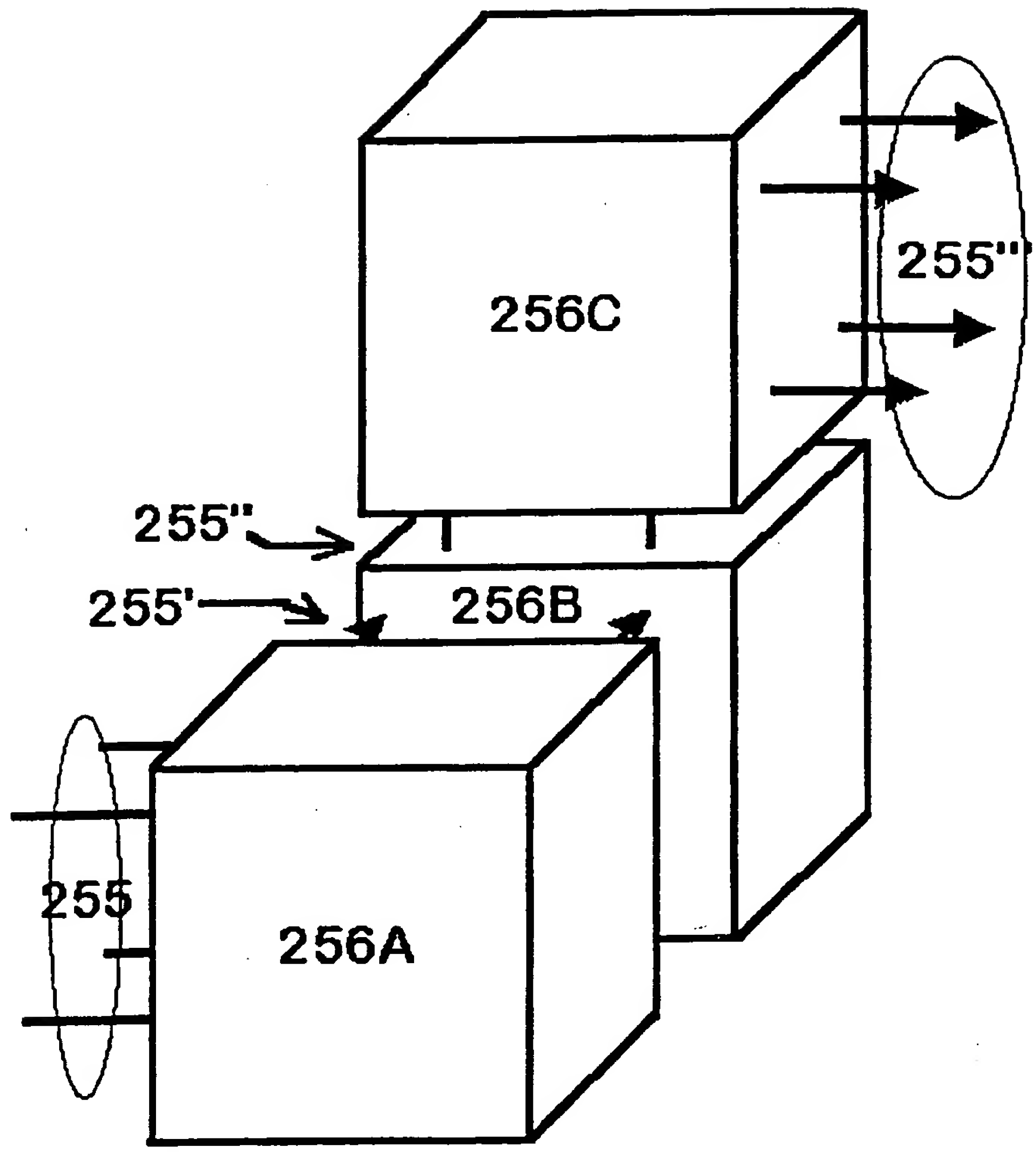


Figure 25c

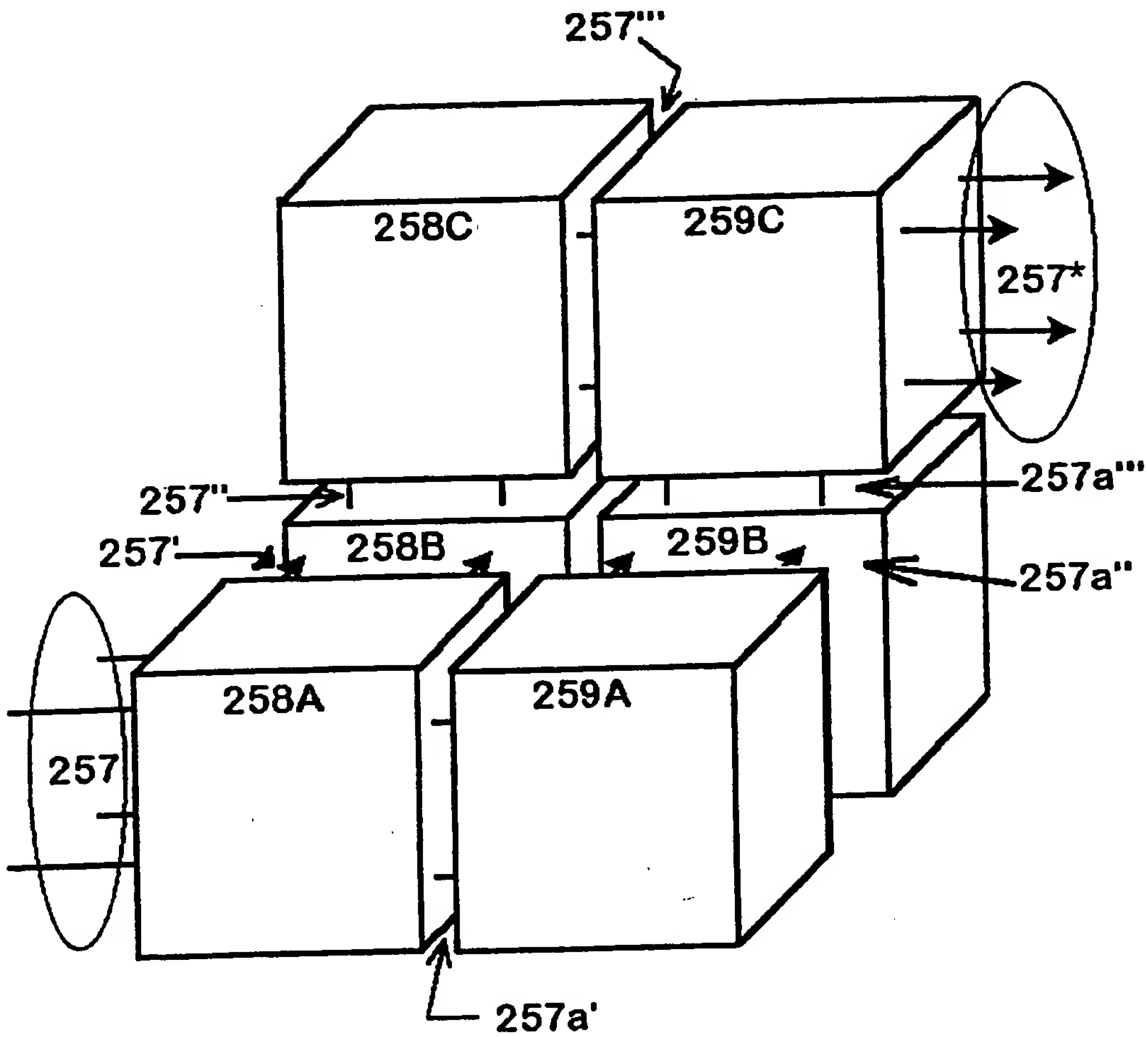

257'''
258C
259C
257*
257''
257a'''
257'
258B
259B
257a''
258A
259A
257
257a'

Figure 25d

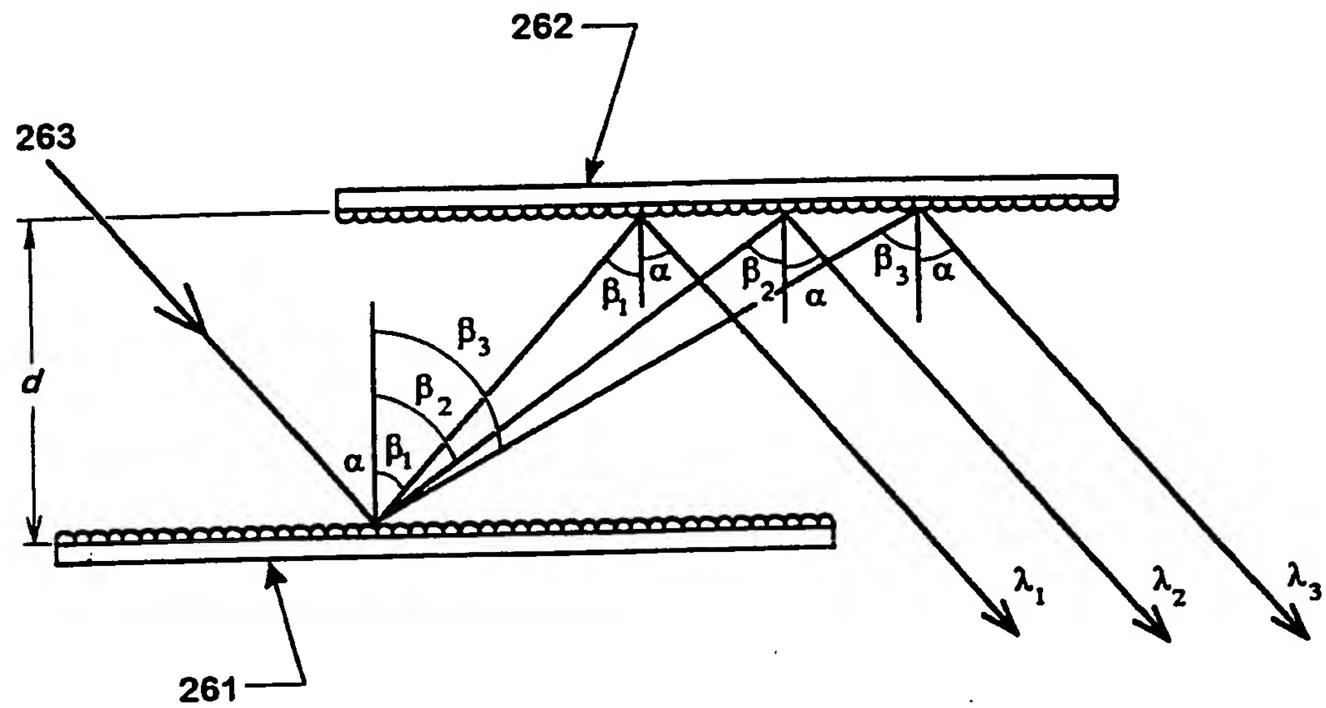

262
263
d
β_3
β_2
β_1
α
β_1
α
β_2
α
β_3
α
λ_1
λ_2
λ_3
261

Figure 26

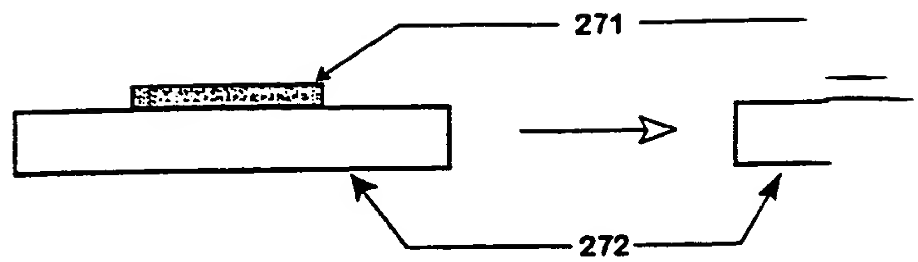


Figure 27a

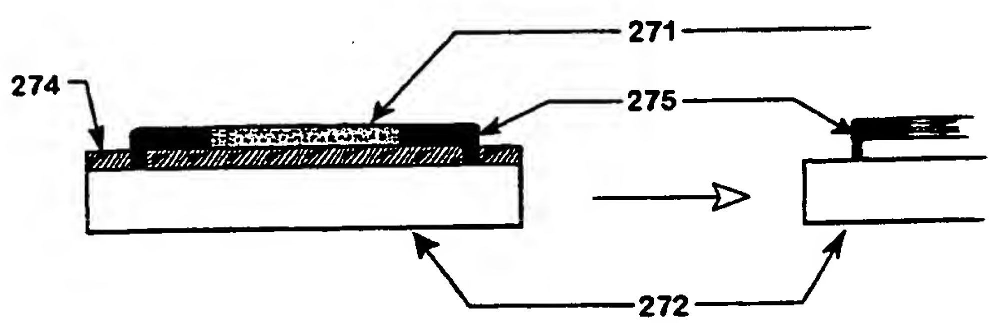


Figure 27c

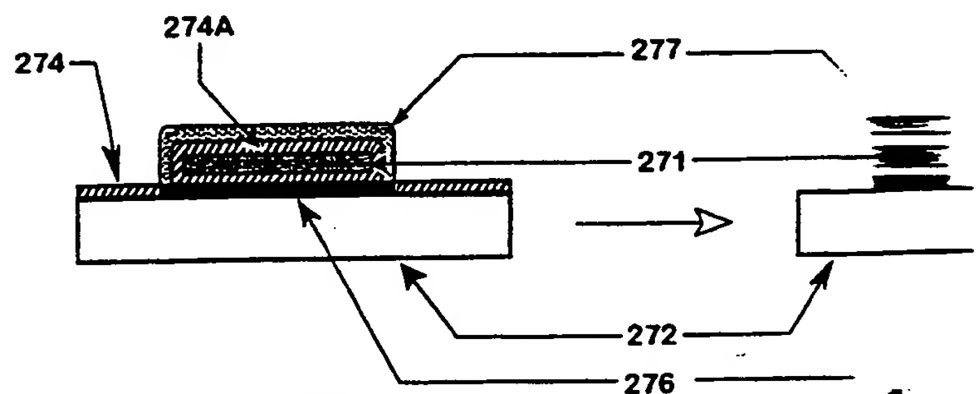


Figure 27e

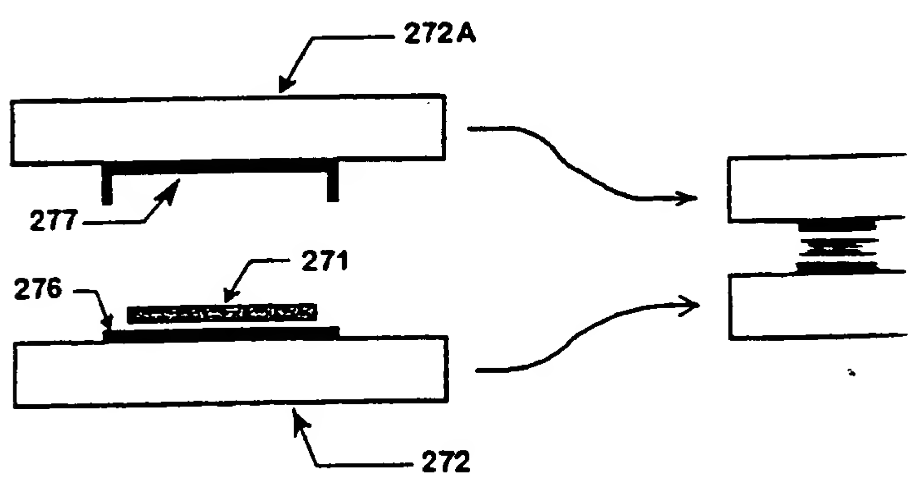


Figure 27g

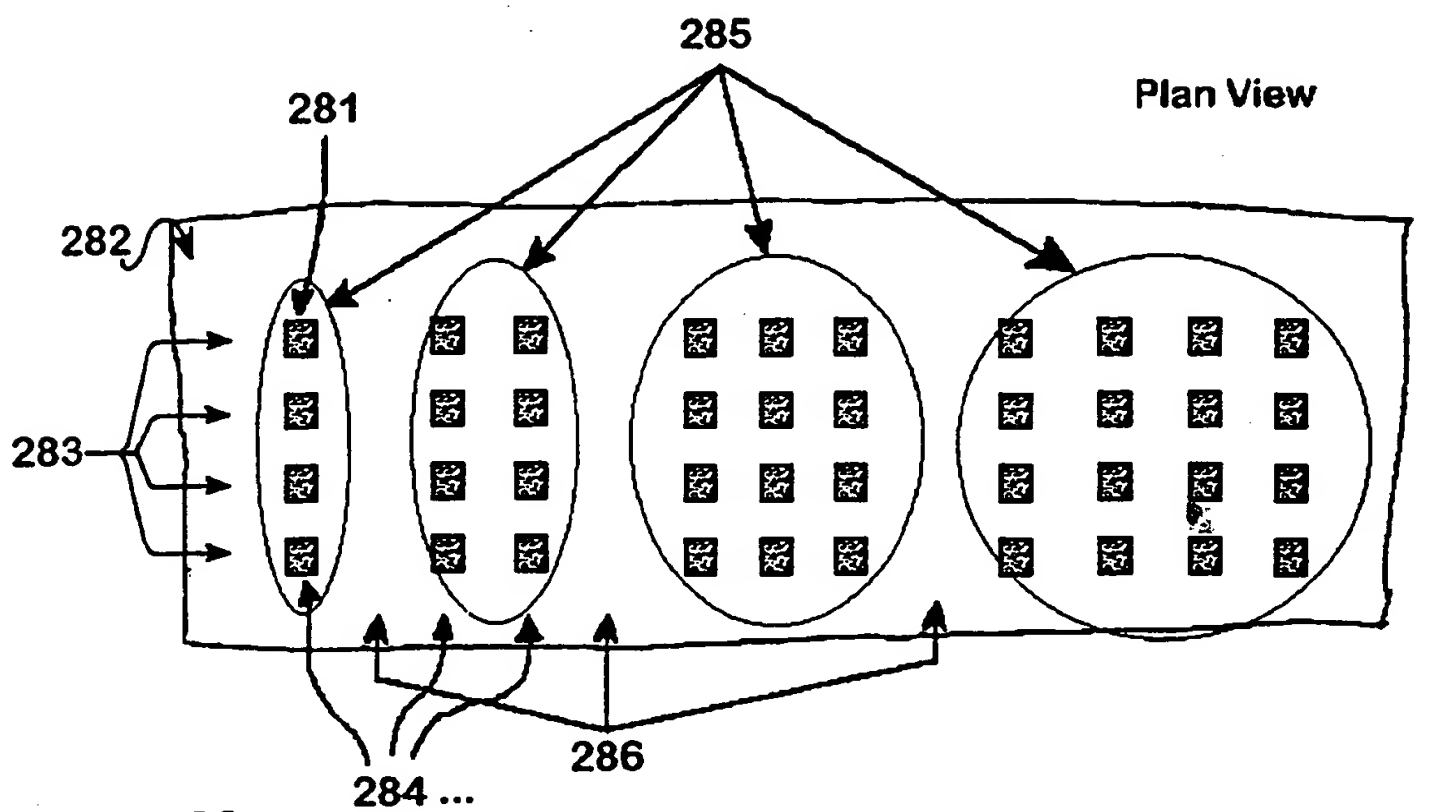


Figure 28a

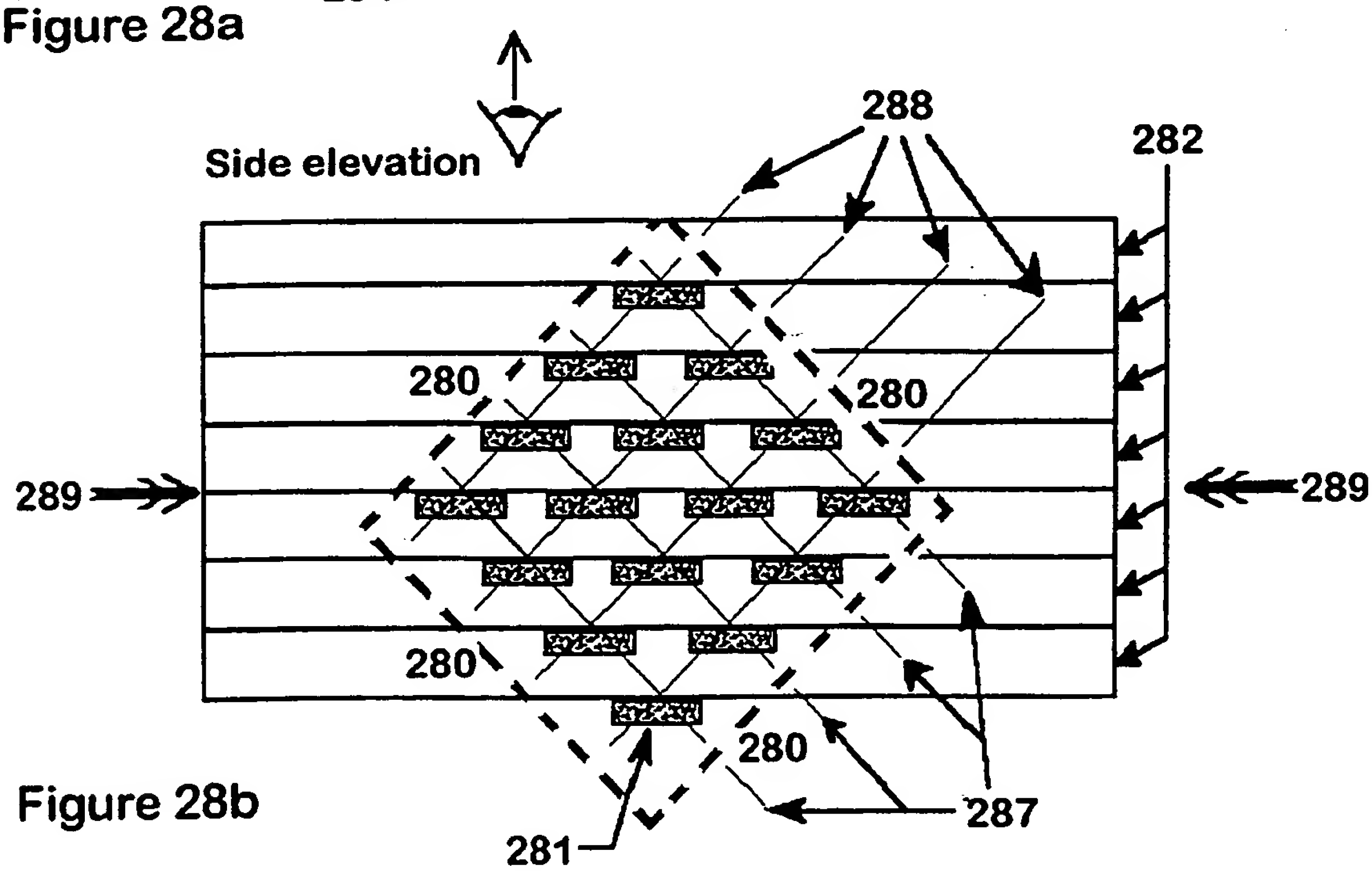


Figure 28b

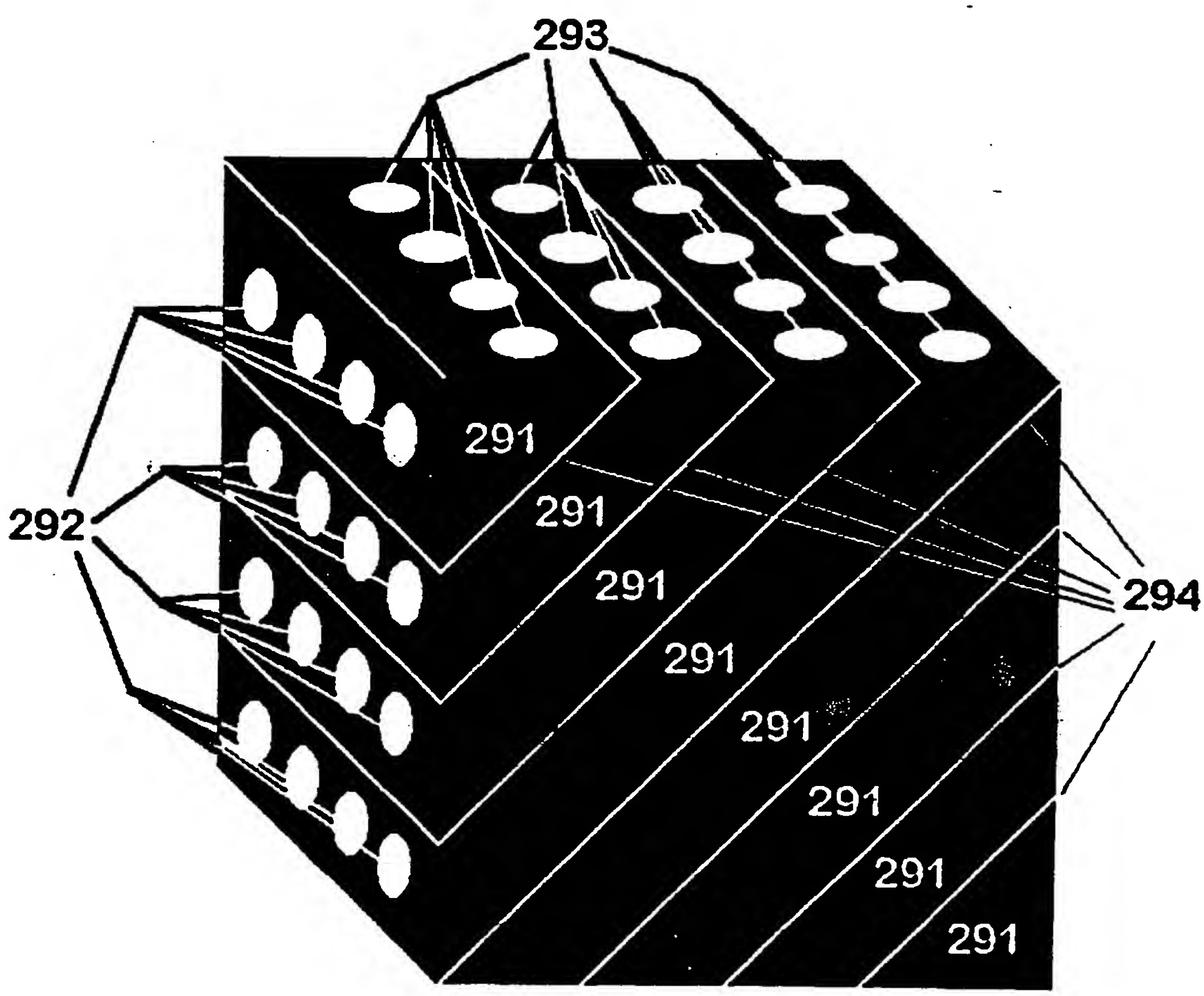


Figure 29

INTERNATIONAL SEARCH REPORT

International application No.
PCT/IL00/00425

A. CLASSIFICATION OF SUBJECT MATTER

IPC(7) :GO2B 6/26
US CL : 385/16
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 385/15-23

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EAST
search terms: optical switch, mirror, reflection, actuation, hinge, spring

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X,P ----- A	US 5,943,454 A (AKSYUK ET AL) 24 AUGUST 1999 (24/08/1999), SEE FIG. 6A.	1 --- 3-8
X ----- A	US 5,742,712 A (PAN ET AL) 21 APRIL 1998 (21/04/1998), SEE FIG. 3A AND 3B.	1 --- 3-8
Y ----- A	US 5,479,064 A (SANO) 26 DECEMBER 1995 (26/12/1995), SEE ENTIRE DOCUMENT, ESPECIALLY FIG. 6.	2 --- 3-8
Y ----- A	US 4,703,215 A (ASANO) 27 OCTOBER 1987 (27/10/1987), SEE ENTIRE DOCUMENT, ESPECIALLY FIG. 1.	2 --- 3-8

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
19 DECEMBER 2000	09 JAN 2001

Name and mailing address of the ISA/US	Authorized officer
Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231 Facsimile No. (703) 305-3230	ELLEN E. KIM Telephone No. (703) 308-4946

INTERNATIONAL SEARCH REPORT

International application No.
PCT/IL00/00425

BOX II. OBSERVATIONS WHERE UNITY OF INVENTION WAS LACKING
This ISA found multiple inventions as follows:

This application contains the following inventions or groups of inventions which are not so linked as to form a single inventive concept under PCT Rule 13.1. In order for all inventions to be searched, the appropriate additional search fees must be paid.

Group I, claims 1-8, drawn to an optical switch.
Group II, claims 9-15, drawn to a hinge.
Group III, claims 16-23, and 49, drawn to a travelling wave actuator.
Group IV, claims 24-29, and 50, drawn to a finger actuator.
Group V, claims 30-31, and 51, drawn to an emergency holding device.
Group VI, claims 32-48, and 52-59, drawn to an electro-mechanical aligning mechanism.
Group VII, claims 60-68, drawn to a method of fabricating a micro-device having a high-quality smooth mirror surface.
Group VIII, claims 69-70, drawn to a mechanism for providing a strictly non-blocking switching configuration and its method of making it.

The inventions listed as Groups I-VIII do not relate to a single inventive concept under PCT Rule 13.1 because, under PCT Rule 13.2, they lack the same or corresponding special technical features for the following reasons: each group of inventions comprises specific elements and those specific elements are different from that of different group of inventions.